Examining copper supply feasibility in decarbonization pathways: a mine-level dynamic approach

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Abstract

Primary copper production capacity is a major concern in light of estimates of future demand. This issue is not sufficiently taken into account in models providing decarbonization pathways. Our study assesses the feasibility of SSPs basic drivers for primary copper requirements derived from the DyMEMDS model, alongside our projections of primary copper production capacities. We introduce a methodology for projecting primary copper production capacities based on a mine-by-mine analysis, including industrial constraints and reserves of each mine. Our results highlight a mismatch between primary copper requirements and production capacities, which could have a significant impact on the technology deployments required to keep pace with socioeconomic assumptions. We suggest that the decarbonization pathway modelling community align their scenarios with extractive industry constraints and consider resource efficiency strategies in order to propose more consistent scenarios to decision-makers, thereby mitigating the risk of climate action being slowed down by a copper supply shortage.

Keywords

Copper; Shared Socio-economic Pathways (SSPs); Mine supply; Decarbonization pathways; Material flow analysis (MFA); Critical minerals

1. Introduction

Copper is at the very heart of energy transition efforts towards the decarbonization imperative, from electromobility and the development of renewable energies to transport and storage infrastructures for low carbon electricity (IEA, 2021, 2024b; Klose & Pauliuk, 2023; Schipper et al., 2018; Watari et al., 2020, 2021). Its demand is set to increase significantly, with the International Energy Agency (IEA) projecting a 57% rise from 2023 to 2050 in the "Net-Zero Emissions by 2050" scenario (IEA, 2024a). Although many uncertainties remain, it is reasonable to assume that similar trends will be observed for copper as for other ferrous and non-ferrous metals, driven by structural factors such as population growth, GDP and urbanisation (Watari et al., 2021). However, copper could face a production deficit from primary sources, as current and planned projects are insufficient to cover resource requirements between now and 2035 (20 Mt primary supply versus 27 Mt primary demand in Announced Pledges Scenario) (IEA, 2024b). Numerous constraints hinder the development of new mines: ore grade quality is globally declining (Northey et al., 2014), the number of discoveries of major deposits has been diminishing over the last decade, due to the reduced availability of resources and shrinking exploration budgets (DeCoff, 2024; Schodde, 2017), threats to land-connected peoples give rise to socio-political resistance (Anguelovski, 2011; Dunlap, 2020; Owen et al., 2022; Rorato et al., 2020; Valenta et al., 2019), and 52% of current mining sites are located in high water stress areas (IEA, 2024b). One of the most emblematic recent examples of the now decisive influence of these “non-geological” variables on primary copper supply was the closure of the Cobre Panama mine in 2023, following a decision by Panama's Supreme Court that the mine was unconstitutional.

In the past decade, academics have increasingly paid attention to production constraints (Watari et al., 2020). Three different approaches have been employed, which could be classified either as top-down, bottom-up or hybrid. The top-down approach consists in evaluating future copper production by assessing its relationship with development variables, and extrapolation from past trends (Schipper et al., 2018). It often relies on forecasting copper supply through a Hubbert linearization of production on ultimate recoverable resources estimates (Calvo et al., 2017; Sverdrup et al., 2017). Although conceptually elegant, top-down approaches are criticised for neglecting future production ramp-up due to the optimisation of extraction techniques, and hence the reduction in extraction costs, as a result of technological progress (Vidal et al., 2019). Therefore, bottom-up studies – mine or basin-level aggregation of production and consumption data – have enjoyed a significant boom, see for instance (Northey et al., 2014, 2023). Building on the maturation of Industrial Ecology (IE), bottom-up approaches have greater accuracy, and greater flexibility to address process-dependent aspects of mineral extraction, but require a significant amount of data (Schipper et al., 2018). Hybrid approaches have also been proposed as a way to combine advantages and drawbacks of top down and bottom-up approaches (Ali et al., 2017; Örtl, 2018; Sverdrup et al., 2019; Vidal et al., 2019, 2021).

While progress on modelling copper production and consumption has been made, the implications for decarbonization pathways have not yet been made explicit. One reason is that the methodological tools to produce decarbonization pathways–such as Integrated Assessment Models (IAMs) (Guivarch et al., 2022), Energy system optimization models (ESOM) (Huang & Eckelman, 2022), or Carbon Emission Prediction Models (CEPM) (Jin et al., 2024)– are lacking proper representation of the energy and material flows of the goods and services provided (Delannoy et al., 2024; Pauliuk et al., 2017). While several initiatives are underway to remedy the situation, for instance with MESSAGEix-Materials stock and flow accounting module (Ünlü et al., 2024) or WILIAM material availability constraint on technology deployment (Samsó et al., 2023), more efforts are still needed. Notably, despite the availability of sensitive private data and detailed field-scale bottom-up models, market intelligence such as the S&P Global database (S&P Global, 2022) remains underutilized. This trend stands in contrast to energy research, which has been relying on datasets from Rystad Energy (Mercure et al., 2021) or GlobalShift (Delannoy et al., 2021) for production forecasts. Additionally, although some studies have quantified primary copper requirement and its impact on the required primary copper supply, they have only compared cumulative copper requirement with reserves and identified resources (Schipper et al., 2018; Seck et al., 2020; Valero et al., 2018). This lack of representation of industrial constraints on mining limits the assessment of the alignment between these primary copper requirement scenarios and future extraction capacities.

Our study aims to confront metal supply projections with demand induced by technology deployment in decarbonization pathways. More specifically, we aim to assess the primary copper requirement feasibility of the Shared Socio-economic Pathways (SSPs) basic drivers by looking at short to medium term industrial constraints on primary copper production capacities. We introduce a methodology for projecting primary copper supply based on a mine-by-mine analysis. Based on data from the International Copper Study Group (ICSG) (ICSG, 2022), our analysis is therefore based on a technico-economic conception of resource availability, i.e. on the availability of proven and probable reserves, and not on identified resources or Ultimate Recoverable Resources, as in previous studies (Calvo et al., 2017; Schipper et al., 2018; Seck et al., 2020; Sverdrup et al., 2019; Valero et al., 2018). Although more conservative, this original approach allows us to take better account of the constraints on copper supply in decarbonization pathways. We have developed primary copper requirement scenarios from the SSPs using a stock-flow industrial ecology model. Finally, we propose a stock-and-flow module to assess the feasibility of decarbonization pathways in light of primary copper production capacities.

2. Materials and methods

2.1. Model overview

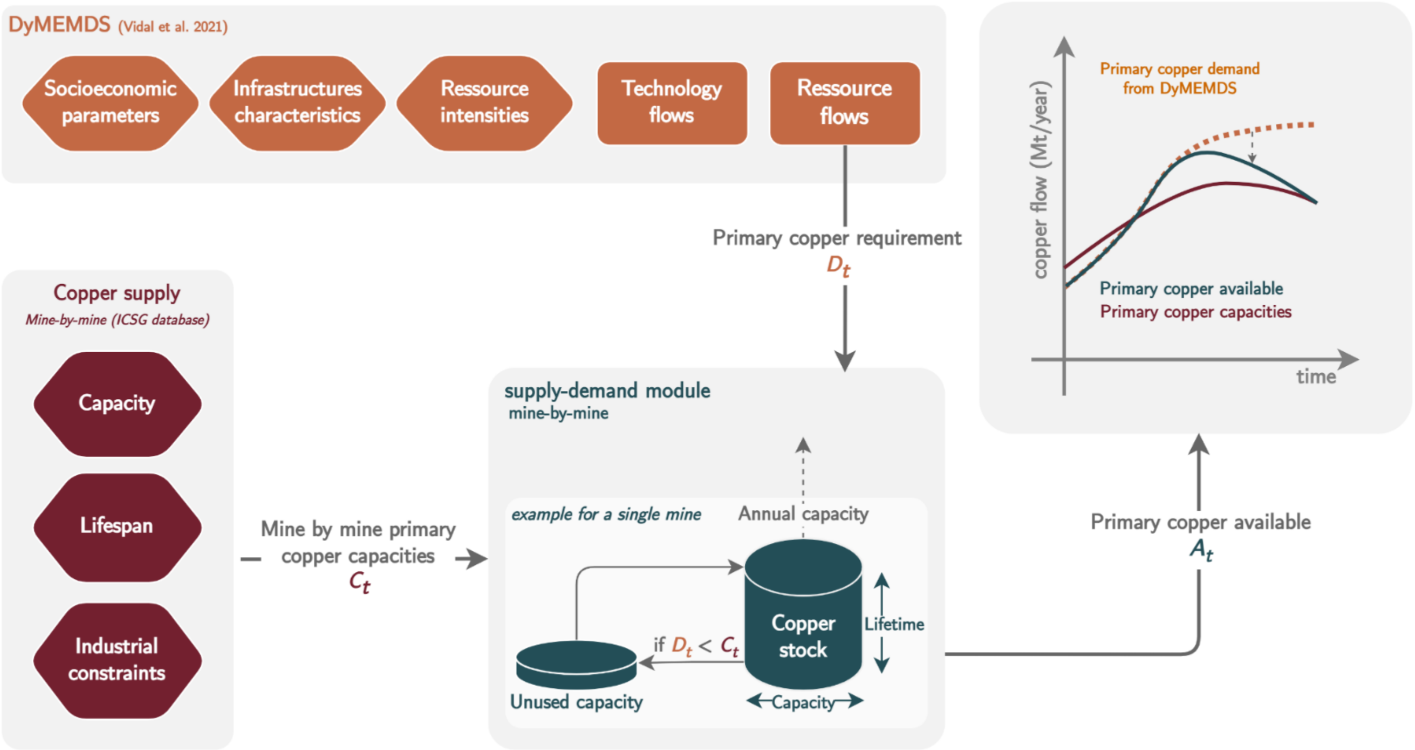

Figure 1| Model overview. Primary copper requirements are derived from the DyMEMDS model (orange), primary production capacities are derived from analysis of the ICSG database (red), and the supply-demand module is used to obtain available primary copper (blue).

Figure 1 provides a general description of models and their interactions. The model aims to simulate the interaction between supply, corresponding to the annual capacities of operational copper mines, and demand for primary copper. The modelling of primary copper requirement (D_t) comes from the DyMEMDS model (Vidal et al., 2021), which integrates exogenously the socio-economic assumptions of the Shared Socio-economic Pathways and the resource intensities of technologies. The functioning of the model is described in Section 2.3. The supply of primary copper is projected from the mine-by-mine dataset of the International Copper Study Group (ICSG, 2022). The methodology is described in Section 2.2 and detailed in Section 2 of the Supplementary Materials. These projections are describing primary copper production capacities (C_t) on a mine-by-mine basis. The supply-demand module is described in Section 2.4. It allows for the interaction between the operating production capacities and requirements of primary copper. It thus determines the available quantity of primary copper (A_t) for each year between 2020 and 2050.

2.2. Primary copper production capacities modelling

We base the modelling of copper extraction capacities on the ICSG dataset titled "*Directory of Copper Mines, Smelters and Refineries - Capacities*" (ICSG, 2022). As this dataset is private, we are unable to distribute it in detail. However, a description of the contents of the dataset is provided in the Figures D & E and Tables B & C in the Supplementary Materials.

This study is limited to the copper contained in productions exiting the mining site; constraints associated with the rest of the value chain (refining, semi-finished products, finished products) are not considered. Production capacities represent the maximum quantity of copper that a mining site can extract each year (expressed in kt/year) and are constrained by various factors. These factors include geological aspects (e.g., type of ore, grade, accessibility, etc.), technical and economic aspects (e.g., reserves, production costs, technologies), and the sizing of the production infrastructure (e.g., crushing, concentrator, vehicles, human resources, etc.). Globally, the ICSG estimates that the utilization rate of mining capacities was approximately 82% between 2020 and 2023, corresponding to the ratio of actual production to production capacity (ICSG, 2024).

Our modelling approach describes production capacities on a mine-by-mine basis. We model each mine as a copper stock (kt) characterized by an annual maximum production capacity flow (kt/year) and an operational lifespan (years).

Our methodology for projecting copper production capacities varies according to the stage of the mining sites, whether they are in operation, undergoing expansion, in development, in feasibility study, or in exploration (detailed information regarding the methodology, parameters, and equations is provided in Section 2 of the Supplementary Materials).

We project operating mining sites based on their closure date as provided by ICSG monitoring or through an analysis of the activity reports of mining companies (see Table E in Supplementary

Materials). When a closure date is not available, we determine a mine’s lifespan using the ratio of proven and probable reserves to the site’s average capacity (see Figure H in Supplementary Materials). For mines for which reserve data is not available (25% of global capacity in 2022), we adopt the global trend by aggregating characterized mining capacity and calculating the annual rate of change. For mining projects in expansion and development, as previously mentioned, we use probable and proven reserves to determine the mine's lifespan if no closure date was found in the ICSG dataset or grey literature.

Regarding the commissioning and closure of mines, we apply a three-year constraint for ramp-up. This assumption is based on our analysis of the ICSG dataset and mining industry activity reports, and is slightly more optimistic than in the work of (Mohr, 2010; Northey et al., 2014), who applied a four-year ramp-up. The ramp-down is modelled more gradually (see Figure J and Table F in Supplementary Materials), based on our analysis of the production plans from several mines (Andrew Issel et al., 2023; Carmelo Gomez Dominguez et al., 2021, 2023, 2024; David Gray et al., 2019, 2020; James Young et al., 2023, 2024; OreWin, 2023; Rodrigo Maureira et al., 2022).

We differentiate mining projects at the feasibility study stage into three cases (low optimism case, middle optimism case, high optimism case), reflecting varying levels of optimism regarding the commissioning of these sites. The low optimism case only considers mining projects with a characterized operational lifespan and confirmed feasibility. The middle optimism case also includes projects with a defined lifespan but where local issues (e.g., permits, disputes) cause delays. For feasibility study projects with unknown opening and closure dates, we employ a logistic function (see Figure K and Table J in Supplementary Materials) for commissioning with different levels of conversion to operational mines and a reduced time before commissioning, depending on the case's level of optimism.

For mining sites in the exploration phase, the ICSG dataset does not provide information on capacities or on start and end dates of operation. We replicate the conversion trends from a discovered deposit to an operational mine (see Figure L in Supplementary Materials). We base our modelling on historical data from MineX Consulting (Schodde, 2017). The parameters of the logistic function for commissioning an exploration-phase site also vary by case to reproduce historical dynamics (see Table L in Supplementary Materials).

2.3. Copper requirement modelling

DyMEMDS (Dynamic Modelling of Energy and Material Demand and Supply) is a bottom-up, stock and flow model linking the evolution of energy demand and production, the development of technological infrastructures, CO2 emissions and raw material demand from 1950 to 2060. The model used in this study is an extension of the sectoral modules used in Le Boulzec, (2022); Le Boulzec et al., (2022) and Andrieu, (2023). The model is built in the Vensim environment. DyMEMDS operates at the global, world regions and country scales for a wide range of technologies from the end-use sector (transportation, building, appliances and electronic devices) to the agriculture, industry and the energy supply chain (supply, transportation and distribution). The methodology implemented to estimate the total requirements for copper lies in successive steps.

In the initial stage, logistic curves are used to represent the evolution of technology stocks as a function of gross domestic product (GDP) and population (Vidal et al., 2021). This approach aims to reproduce a diverse array of historical data observed across different countries, utilizing a uniform set of equations and a limited number of input parameters, with calibration based on technology levels in 2015. In the subsequent stage, the estimated technological stocks serve as inputs to a material flow analysis which ultimately facilitates the estimation of material stocks for each technology using material intensities - measured in kilograms of copper per technological unit. In the final stage, the model also estimates the embodied energy and CO_2 emissions associated with these infrastructures, although these aspects are not part of the present study. The DyMEMDS model is further described in Andrieu, (2023); Le Boulzec, (2022); Le Boulzec et al., (2022); Vidal et al., (2022). A description of the technologies and sectors modelled in our study is provided in Table A of the Supplementary Materials.

We used the Shared Socioeconomic Pathways projections of basic drivers (population and GDP, by country) to run DyMEMDS. These data are provided by IIASA (https://data.ece.iiasa.ac.at/ssp/) in collaboration with the work of the Wittgenstein Center (KC et al., 2024) and Vienna University of Economics and Business (Crespo Cuaresma, 2017). The SSP's global population and GDP projections are illustrated in Figures A, B & C of the Supplementary Materials.

We used International Wrought Copper Council (IWCC) data on end-use sectors (IWCC, 2024) to calibrate global copper requirements (primary and recycling) from DyMEMDS. Following Klose & Pauliuk, 2023, we have aggregated the technologies and sub-sectors corresponding to the IWCC end-use dataset (building, transport, other equipment, industrial, infrastructure). Some modifications have been made to the copper requirements by technology and sub-sector, to match the IWCC aggregated sector rates. The results of this calibration are discussed in Section 3.2.

2.4. Supply-demand interactions module

The model discretizes copper flows and stocks on an annual basis(t). As illustrated in **Figure 1**, each year, the DyMEMDS model exogenously provides a global primary copper requirement D_t. This requirement is compared to the global primary copper capacities C_t for that year within the supply-demand module, depending on the case considered (low optimism case, middle optimism case, high optimism case). Global primary copper production capacities represent the total capacity of all operational mines in a given year. Then, two situations can occur: one in which the primary copper requirement exceeds the global primary production capacities ($D_t > C_t$), and one in which demand is less than or equal to production capacities ($D_t \leq C_t$). In the first situation, part of the requirements is not met, and the entire primary copper production capacity is used. In the second situation, the unused capacities are reintroduced and redistributed among all mines operating in year (t). Unused capacities are redistributed to the first year in which its production capacities are lower than its maximum operating capacity; generally corresponding to the first year of ramp-down before closure. This approach preserves production capacities and stocks using a mass-consistent logic similar to that applied in Material Flow Analysis (Brunner & Rechberger, 2016), thereby extending the duration of the maximum production capacity plateau, and extending the overall lifespan of each mine. All these data are then visualized through graphs displaying the initial primary copper requirement, the initial primary copper production capacity, and the evolution of available primary copper production capacities between 2020 and 2050. The available primary copper production capacity could be considered equivalent to actual primary copper production for each year. Additionally, the model enables the determination of the capacity utilization rate for each year.

3. Results & Discussion

3.1. Primary copper production capacities to 2050

Our initial estimates of global copper mine capacities indicate peak capacities in 2031 (34 Mt), 2032 (36 Mt), and 2039 (39 Mt) for the low, middle and high optimism cases, respectively, as illustrated in **Figure 2**. In line with the IEA analysis, currently operational capacities decrease over time (IEA, 2021, 2024b).

A common finding across all three cases is the inability of future mining projects to compensate for the decline in currently operational production capacities. This issue is particularly pronounced in the low optimism case and persists even under more optimistic assumptions regarding the deployment of capacities from projects in the feasibility study and exploration stages in the middle and high optimism cases. The lead times associated with these phases, along with the number and scale of projects, constrain the expansion of new production capacities. Additionally, capacities under development or expansion have only a minimal impact on overall capacity trends.

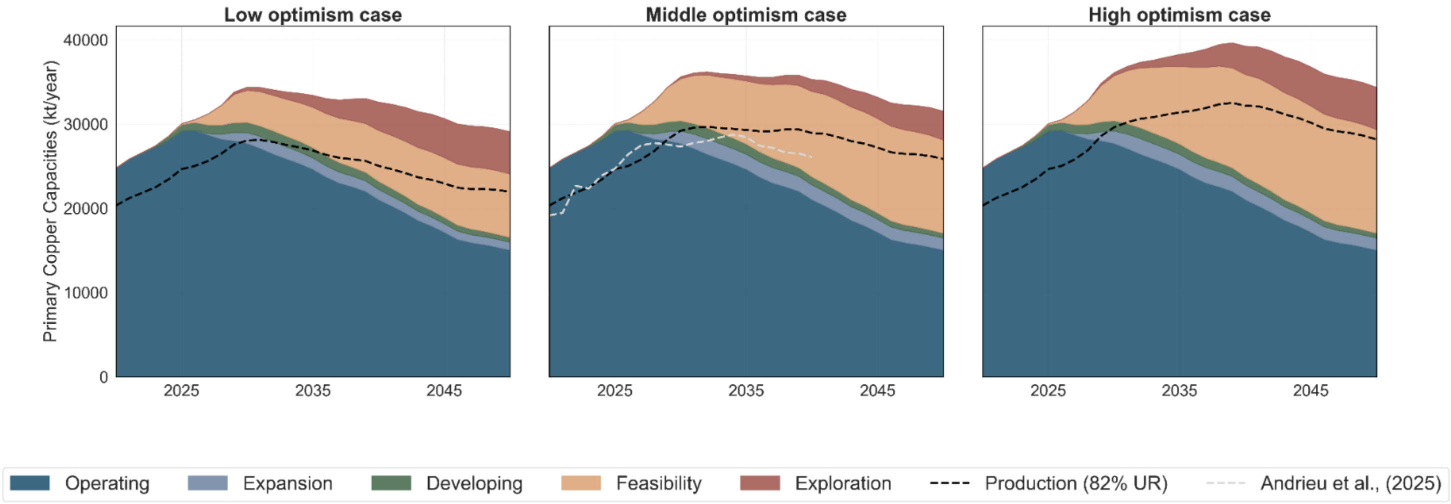

Figure 2| Primary copper production capacities projections (low optimism case, middle optimism case, high optimism case) from 2020 to 2050

We compared our middle optimism case to the analysis of Andrieu et al., (2025), which is based on S&P Capital IQ Pro data. For this comparison, we assumed a capacity utilization rate of 82%, consistent with recent years (ICSG, 2024). Production projections appear similar until peak. The projection by Andrieu et al., (2025) diverges slightly from 2028, but remains close, with a slightly reduced trend until 2040. Regarding geographical distribution of future primary copper capacities, see Figure J in Supplementary Materials.

We compared cumulative primary copper capacities with USGS data, assuming 100% utilization rate. The USGS reports that copper reserves and identified resources amount to 1 billion tons and 2.1 (as of 2015) billion tons, respectively (USGS, 2024). The cumulative primary production capacities between 2020 and 2050 total 921 Mt (low), 1,018 Mt (middle), and 1,079 Mt (high). These results correspond to 92%, 102%, and 108% of the reserves; 44%, 48%, and 51% of the identified resources, respectively.

One limitation of our study concerns the data provided by the ICSG. These data appear robust for operational, expansion, and developing sites, as they accurately reproduce production capacities between 2020 and 2024 when compared with USGS or BGS production data, considering the capacity utilization rate. However, feasibility study projects and particularly those in the exploration phase may be incomplete. This represents a significant methodological limitation in constructing our projections, as future capacities directly depend on the number of projects in development, even though the dynamics of discovering new large deposits remain low (Guj & Schodde, 2025; Schodde, 2017), despite rising copper market prices and increased exploration budgets since 2020 (see Figures N & O in Supplementary Materials). However, these budgets remain well below the peak levels recorded in the early 2010s.

In addition to ICSG data, our study relies on the industrial capacity planning derived from our review of technical and activity reports, as well as the characterization of probable and proven reserves reported by mining companies. This aspect requires careful consideration, as planning may evolve over time. Further research on the historical developments and interactions between production capacities and reserve levels would be necessary to better understand the general trends in a mine’s lifecycle.

The scope of our study is limited to the copper content in the output products from a mining site (concentrate, cathodes for SX-EW units). Constraints related to the downstream value chain are beyond our scope. In the case of copper, our analysis led us to focus on mining extraction; however, this is not necessarily the primary area of concern for all critical minerals. For instance, in the nickel EV supply chain and NMC Li-ion battery chemistry, long-term bottlenecks are more related to nickel sulfate and intermediate products such as mixed hydroxide precipitate (MHP) rather than laterite ores.

Our projections do not account for the possibility that some mining sites may reduce or temporarily cease production when market prices are low, or more permanently during "care and maintenance" periods. In our future production capacity projections, no "care and maintenance" phase is modelled, which could result in an overestimation of available capacities each year.

At this stage of our research, we assume that differences between supply and demand do not influence production capacity. This assumption appears relevant in the short term, as there is typically a significant delay (several years) between a sustained favourable price signal and the increase in production capacity at an existing mining site. Indeed, the commissioning of mining infrastructure that increases production capacity is subject to constraints such as legal authorisations, feasibility studies, the design and construction of production infrastructure, and start-up. This logic also applies to undeveloped deposits. Furthermore, the projections (low optimism case, middle optimism case, high optimism case) can also be understood as projections in which the economic context is more or less favourable to investment decisions in the copper sector. Using the high optimism case would allow us to bypass modeling future production capacities endogenous to the market price for copper. However, consideration of the market price is insufficient in the context of an investment decision; it is also necessary to integrate social, political, geopolitical, and ecological components.

However, copper price influences the exploitable reserves at an active mining site. Alongside with treatment and refining charges (TC/RC, *i.e.* the amount paid by miners to smelters when they sell concentrates - lower TC/RCs indicate higher constraints on ore availability-), this price partly reflects the balance between the supply and demand for copper. As a result, a mined deposit sees its proven and probable reserves either increase or decrease. This factor is not accounted for in our analysis, as it would require detailed data on the characteristics of each extraction site (cut-off, reserves, extraction costs). All these parameters would need to be adjusted as a function of the market price. A more global approach, akin to a market price sensitivity analysis, can be considered by applying reduction or increase factors to the reserves of operating sites based on an empirical analysis of industrial actors' behaviour in response to a significant variation in the price of copper. Consequently, our model also fails to take into account the impact of copper price instability/volatility (and thus the degree of uncertainty regarding future revenues from mining) on the development of production capacity.

3.2. Primary copper requirement scenarios to 2050

Primary copper requirements for the Shared Socioeconomic Pathways (SSPs), as estimated from the DyMEMDS model, are illustrated in **Figure 3**, which shows demand for each aggregate sector described in the IWCC dataset (IWCC, 2024). The scenarios are globally aligned with the historical copper mining data provided by ICSG Copper Factbook 2024 (ICSG, 2024). Prior to 1990, the scenarios slightly underestimate the primary copper requirement. The SSP1 scenario shows an overestimation of the primary copper extracted between 2000 and 2023, followed by a more significant upward trend from 2030 to reach 77 Mt/year in 2050. The SSP2 and SSP4 scenarios closely follow the historical trend until 2035, after which demand growth increases to reach approximately 51 Mt/year (SSP2) and 41 Mt/year (SSP4) by 2050. The SSP3 scenario slightly underestimates historical demand for primary copper for the period 2015-2023 and follows a slightly lower trend thereafter to reach 28 Mt/year in 2050. The SSP5 scenario forecasts rapid and sustained growth in demand for primary copper, which is not in line with historical trends and which overestimates demand for primary copper over the period 2000-2023, reaching 88 Mt/year in 2050. The figures concerning copper requirements from recycling and overall requirements (primary and recycled) are shown in the Supplementary Materials (Figures Q & R).

We have compared the results of our scenarios with two previous studies (Klose & Pauliuk, 2023; Schipper et al., 2018) that focus on copper and Shared Socio-economic Pathways, as shown in **Table 1**. The copper requirements (primary + recycling) are significantly higher in 2050 than these studies for the SSP1, SSP2 and SSP5 scenarios. In contrast, SSP3 is lower than in (Schipper et al., 2018). It appears that DyMEMDS is more sensitive to the differences in terms of GDP per capita between the SSPs (see Figure C in Supplementary Materials).

The recycling rate has a major impact on the total amount of primary copper required to meet the demand for copper needed to deploy technologies. As the stock of copper increases in the global economy, copper from recycling rises in all five SSPs, from 7 Mt in 2020 to 33 Mt for SSP1, 25 Mt for SSP2, 19 Mt for SSP3, 22 Mt for SSP4 and 36 Mt for SSP5 in 2050. We assume a more conservative estimate than (Schipper et al., 2018), showing primary copper requirement with a 90% recycling rate, to be consistent with historic primary copper mining production. As a result, in all five SSPs, demand for primary copper is higher than in these two studies, even for SSP3. For SSP2, our result is quite similar to the (Klose & Pauliuk, 2023) study, but diverges to reach 51 Mt compared to 30 Mt in 2050 for this previous study.

The results of aggregate sector calibration on the basis of IWCC end-use copper requirement works well for building construction, transport and infrastructure, as illustrated by Figure S in Supplementary Materials. The sum of industrial and other equipment aligns with the IWCC distribution, but it is distributed differently in the DyMEMDS aggregation. This is due to the three sub-sectors: mechanical engineering, military, chemical production (see Table A in Supplementary Materials) are integrated into industry, though part of which could be attributed to Other Equipment.

		SSP1		SSP2		SSP3		SSP4		SSP5	
		2035	**2050**	**2035**	**2050**	**2035**	**2050**	**2035**	**2050**	**2035**	**2050**
Copper requirements (primary + recycling) (Mt/year)	(Schipper et al., 2018)	50	67	47	64	45	55	47	62	50	67
	(Klose & Pauliuk, 2023)	-	-	35	44	-	-	-	-	-	-
	This study	53	109	42	76	34	47	38	63	58	124
Primary copper requirements (Mt/year)	(Schipper et al., 2018)	22	31	19	25	18	19	19	25	22	29
	(Klose & Pauliuk, 2023)	-	-	26	30	-	-	-	-	-	-
	This study	38	77	29	51	22	28	26	41	43	88

Table 1| Comparison of DyMEMDS results (2020 - 2050) with previous studies. (Schipper et al., 2018) is characterized by a stock dynamics method, driven by SSPs GDP and population assumptions, with disaggregated products. (Klose & Pauliuk, 2023) is characterized by a dynamic material stock and flow model, driven by SSP2 GDP and population assumptions, with an energy supply system compatible with RCP2.6, and disaggregated products. This study is characterized by a dynamic material stock and flow model, driven by SSPs GDP and population assumptions, with disaggregated products.

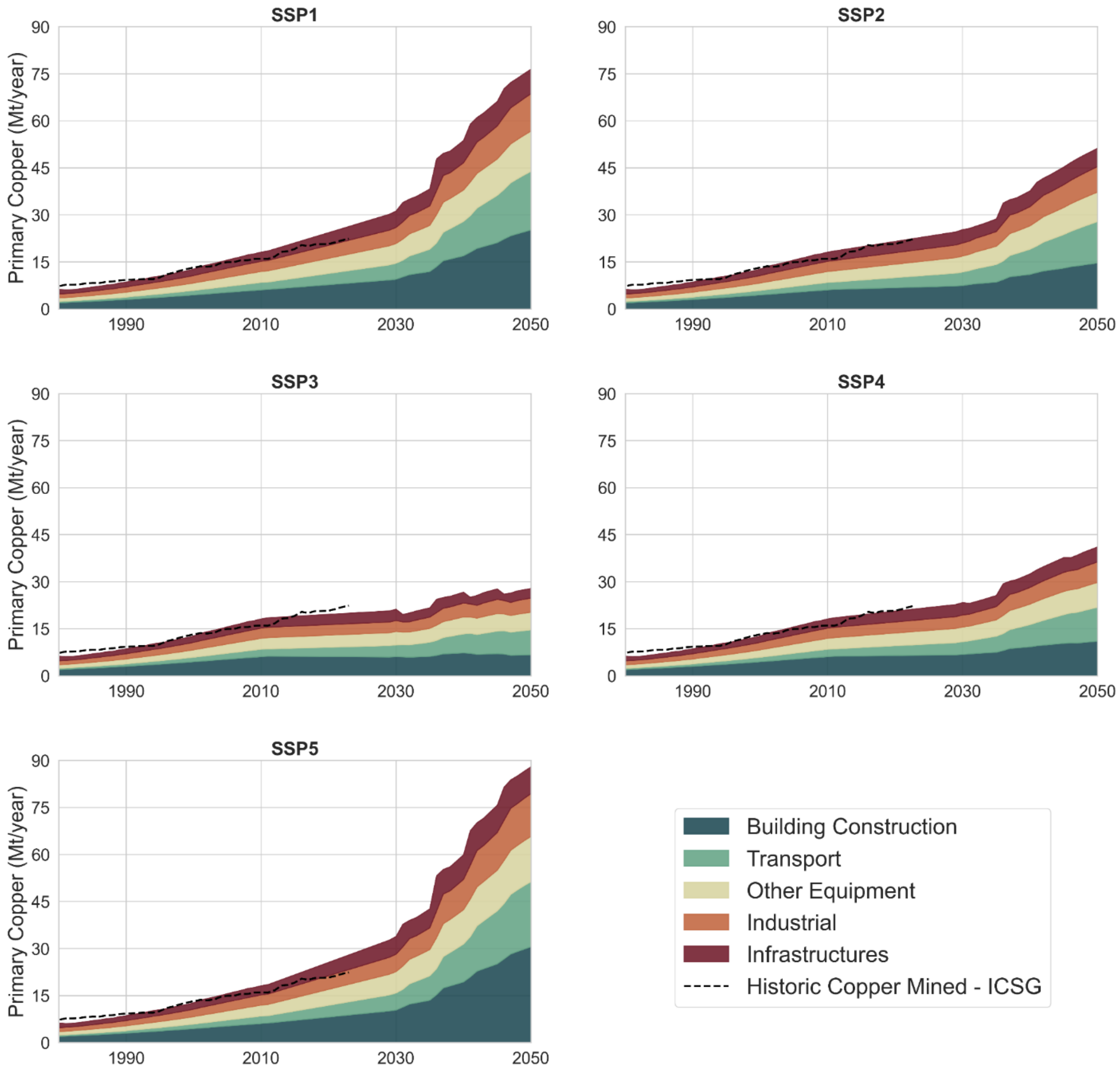

Figure 3| Primary copper requirements in the Shared Socioeconomic Pathways resulting from the DyMEMDS model

To identify which technologies or sub-sectors will have the highest copper demand, or experience significant increases between 2020 and 2050, we have summarized in **Table 2** the main copper-consuming sectors (representing more or less 80% of copper requirement). We observe that historical sectors such as construction, other equipment, other industrial sectors, electricity transport and light internal combustion vehicles are predominant. This is partly due to the development of low-income and middle-income regions, where GDP per capita is rising and basic needs are developing for access to decent housing, electricity and a mobility network, as well as the maintenance of existing facilities in high-income countries. Copper requirements for clean technologies are mainly driven by electromobility such as light battery electric vehicles and batteries and also electricity transport, in line with Klose & Pauliuk's findings on SSP2 RCP2.6 and the IEA's analysis of copper requirements for clean technologies (IEA, 2021, 2024b; Klose & Pauliuk, 2023).

Technologies or subsectors	Copper requirement in 2050 (Mt/year)									
	SSP1		SSP2		SSP3		SSP4		SSP5	
	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050
Building	9.4	30.7	8.4	18.9	7.7	10.0	8.1	14.8	9.8	36.6
Diverse equipment	5.6	17.8	5.1	12.4	4.7	7.6	4.9	10.3	5.8	20.2
Light Battery Electric Vehicle	0.28	12.7	0.24	9.4	0.23	6.4	0.23	8.0	0.26	14.0
Other Industrial sectors	3.5	12.3	3.2	8.4	2.9	5.0	3.1	6.9	3.6	14.0
Electricity Transport	3.3	6.9	3.0	5.2	2.8	3.0	2.9	4.4	3.5	7.5
Light Internal Combustion Vehicle	2.7	5.1	2.4	3.8	2.3	2.5	2.4	3.2	2.6	5.7
Battery Electric Vehicle	0.54	3.6	0.51	2.4	0.48	1.3	0.49	2.0	0.55	4.0
Total	*25.3*	*89.1*	*22.9*	*60.5*	*21.1*	*35.8*	*22.1*	*49.6*	*26.1*	*102.0*
Rate compared with all sectors	*77%*	*82%*	*77%*	*80%*	*77%*	*76%*	*77%*	*79%*	*77%*	*82%*
Total (all sectors)	**32.7**	**109**	**29.6**	**76**	**27.5**	**47**	**28.6**	**63**	**34.0**	**124**

Table 2| Main technologies and sub-sectors by copper requirements for DyMEMDS SSP results, for 2020 and 2050

Our results provide an overview of future copper requirements based on different GDP per capita evolutions across the five Shared Socioeconomic Pathways (SSPs). However, to describe these scenarios more accurately, several improvements should be considered. Firstly, the building and other equipment sectors need to be disaggregated to better understand the origin of copper requirements. Nevertheless, we lack disaggregated data on material intensity for the building and other equipment sectors. Thereafter, we could integrate the shares of technologies associated with the future trajectories proposed by the IAM community. This would allow us to better align with the narratives of the SSPs and to understand the impact of the technologies required to achieve decarbonization pathways on copper requirements.

3.3. Feasibility of scenarios

The results of the assessment of SSPs' primary copper requirement from DyMEMDS, regarding primary copper production capacity projections (low optimism case, middle optimism case, high optimism case), are illustrated in Figure 4. This figure presents results for a 100% capacity utilisation rate limit, which could be considered optimistic. For SSP1, we observe a capacity utilisation rate exceeding 95% by 2020, followed by a rapid divergence between primary copper requirements and production capacities around 2035 across all three cases. The available primary copper remains very close to the initial production capacities, as the demand does not allow for the redistribution of unused capacities. For SSP2, the demand for primary copper follows a trend that allows production capacities to supply sufficiently across all three cases between 2020 and 2035. The rapid growth in requirements after 2035 leads to a divergence with available primary copper, which shifts over time between the production capacity projections, despite unused stocks between 2020 and 2035. For SSP3, the demand is fully met by available primary copper. Nevertheless, in the low optimism case by the 2050 horizon, requirements exceed initial production capacities and the divergence in trends between requirements and production capacities likely implies a bottleneck post-2050 across all projections. For SSP4, the bottleneck shifts over time depending on the production capacity projections, with requirements for primary copper exceeding production capacities around 2040. For SSP5, the capacity utilisation rate slightly exceeds 100% starting from 2020, with a rapid divergence occurring towards 2030.

In summary, the feasibility of primary copper requirement scenarios derived from GDP per capita in the Shared Socioeconomic Pathways in DyMEMDS is only assured for SSP3 between 2020 and 2050, with major concerns arising by the 2060 horizon. The other copper requirement scenarios exceed the available primary copper between 2030 and 2045, indicating the infeasibility of these scenarios in our assessment.

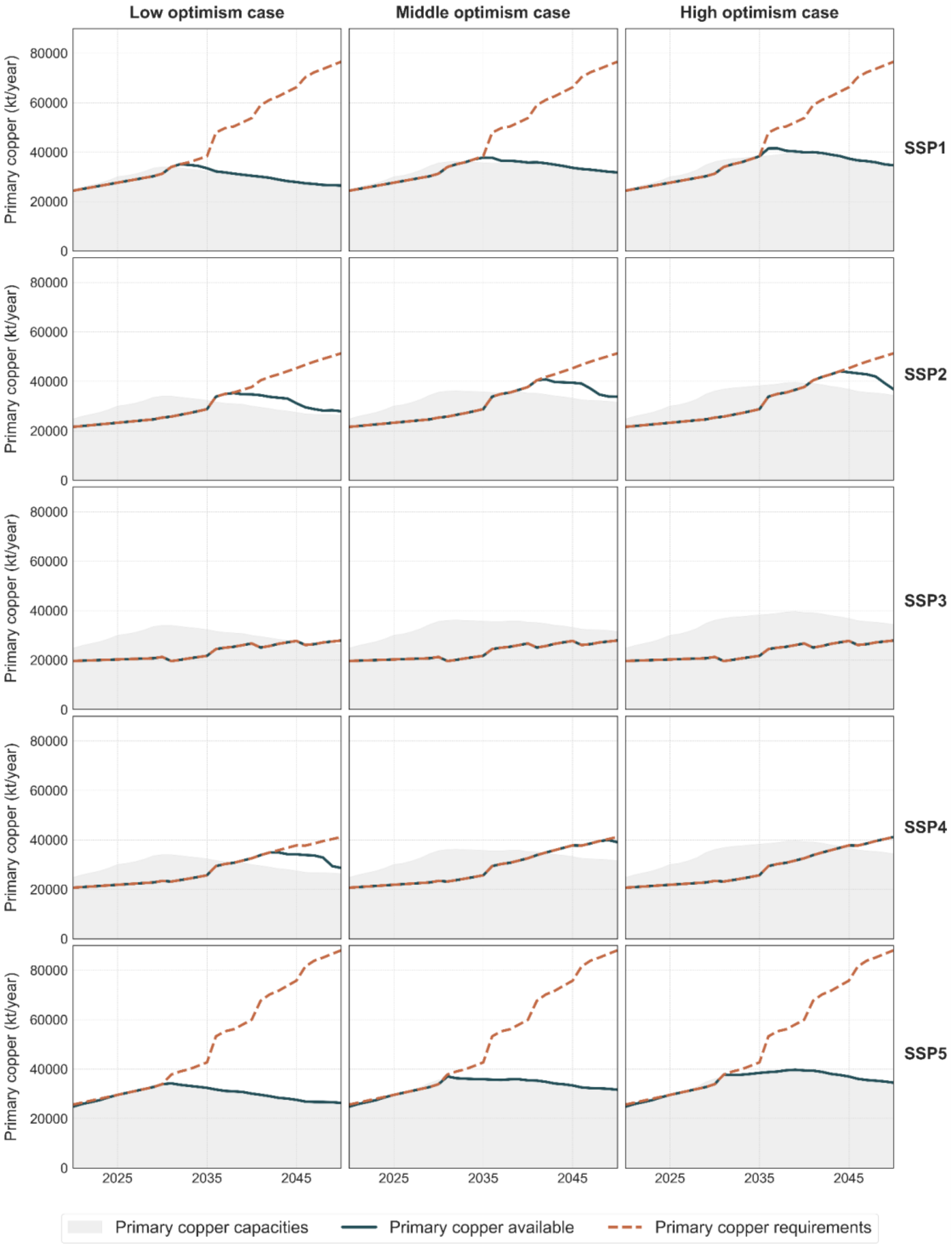

Figure 4| Primary copper capacities, availability and demand, across the Shared Socio-economic Pathways (SSPs).

4. Conclusion & Future development

4.1. Conclusion

Our study presents a method to evaluate the feasibility of primary copper requirement scenarios in relation to primary copper production capacities. These production capacity projections, limited by the industrial constraints of the mining sector, exhibit a peak in production followed by a decline, even under optimistic assumptions regarding mining sites currently undergoing feasibility and exploration studies. The primary copper requirement scenarios, derived from the Shared Socioeconomic Pathways (SSPs) basic drivers and DyMEMDS, demonstrate growth trends correlated with GDP per capita assumptions. The feasibility assessment reveals a mismatch between copper requirements and production capacities, which could significantly impact the technological deployments necessary to follow GDP per capita evolution.

Despite the need for improvements in the representation of technologies in DyMEMDS and the absence of strategies to reduce copper requirements per technology, our findings highlight the potential misalignment between socio-economic assumptions and the industrial constraints of primary copper production capacities.

We underscore the necessity for decarbonization scenarios, proposed by academic research and institutions, to incorporate the quantification of copper requirements (stock and flow) and, more broadly, critical minerals into their modeling frameworks (Pauliuk et al., 2017), either in post or ex-post analyses. The material flows required for the technological deployments envisioned in these scenarios need to be assessed in relation to the industrial constraints of the mining sector, as well as the broader social, environmental, and political dimensions inherent to this sector. Criticality assessment methods could contribute to this assessment. Otherwise, policymakers risk being steered toward trajectories that are virtually unachievable, slowing down the decarbonization of the global economy. It now seems essential to correlate climate change mitigation policies with strategies for the sustainable management of essential minerals, such as circular economy principles, resource efficiency strategies, sufficiency measures and the equitable sharing of global resources.

4.2. Future development

Our future work will focus on evaluating additional primary copper requirement scenarios to assess their feasibility in relation to our primary copper production projections. This review would aim to emphasise the importance of assessing the feasibility of future scenarios to provide decision-makers with a more consistent set of options. It also seeks to engage the decarbonization pathways modelling community to integrate material requirements modules into their models and prioritise decarbonization strategies that align with the industrial constraints of metal mining. This approach could help align these strategies with material sufficiency, efficiency, substitution, and circularity.

Regarding the modelling of copper requirement, we will particularly focus on the reduction in requirements for primary copper resulting from the scenarios of the DyMEMDS model. We aim to address this reduction by estimating the potential of material sufficiency measures, material efficiency of technologies, and the substitution potential of copper in various industrial sectors (Klose & Pauliuk, 2021, 2023; Watari et al., 2022). This study will enable us to evaluate the feasibility of our scenarios in light of strategies to reduce primary copper consumption.

Regarding future production capacities, we aim to capitalise on the mine-by-mine description of our projections. Indeed, we plan to estimate the impacts on production capacities of the social, ecological, and geopolitical components of copper availability. With the help of the EJ Atlas' work on social disputes related to mining projects, we would be able to estimate a reduction in production capacities based on the risk of slowdown or abandonment of mining projects (Scheidel et al., 2020; Temper et al., 2015, 2018). We also plan to study the vulnerability of mining sites to climate change, particularly water stress, which could be analyzed at a global or regional level. This would enable us to evaluate the criticality of copper in a comprehensive manner within prospective scenarios, allowing us to detail and estimate the potential reduction in production capacities based on the characterized risks. This would provide a new perspective on the criticality of copper, counter to the methodologies currently used to evaluate the criticality of minerals.

Finally, we would be able to expand our study's scope by regionally allocating the copper content output from mining sites derived from the projections. This would involve utilising ICSG data on refining sites and data on global copper exchanges. We could design projections in line with the description of Shared Socioeconomic Pathways narratives, particularly the degree of cooperation (O'Neill et al., 2014, 2017).

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Author Contributions

GP: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft; **BA**: Methodology, Writing – review & editing; **OV**: Software, Writing – review & editing; **LD**: Writing – review & editing, Supervision; **HB**: Writing – review & editing; **MG**: Methodology, Writing – review & editing, Supervision; **YG**: Methodology, Writing – review & editing, Supervision, Funding acquisition; **SD**: Methodology, Writing – review & editing, Supervision, Funding acquisition

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data and supplementary information will be made available upon request.

Declaration of AI use

We have used AI-assisted technologies for spellchecking and as inspiration for rewording individual sentences. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Supplementary materials

Examining copper supply feasibility in decarbonization pathways: a mine-level dynamic approach

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1. DyMEMDS description and SSPs assumptions

1.1. GDP from IIASA SSP database

The Figure A shows the GDP trends of SSPs up to 2100.

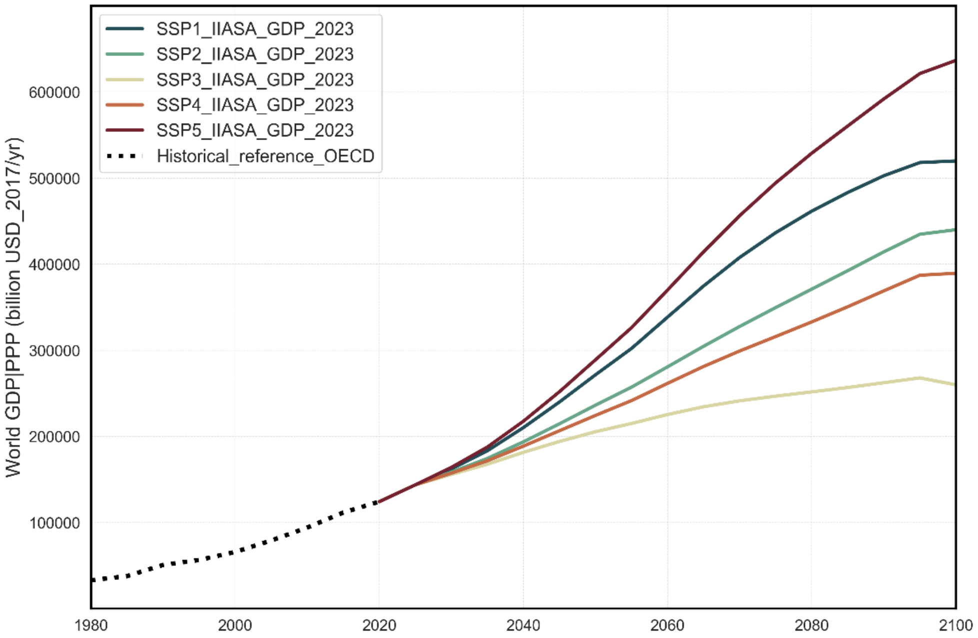

Figure A : GDP in the Shared Socioeconomic Pathways version 3.1

Sources : IIASA SSP database (https://data.ece.iiasa.ac.at/ssp) based on (Crespo Cuaresma, 2017)

1.2. Population from IIASA SSP database

The Figure B shows the global population trends of SSPs up to 2100.

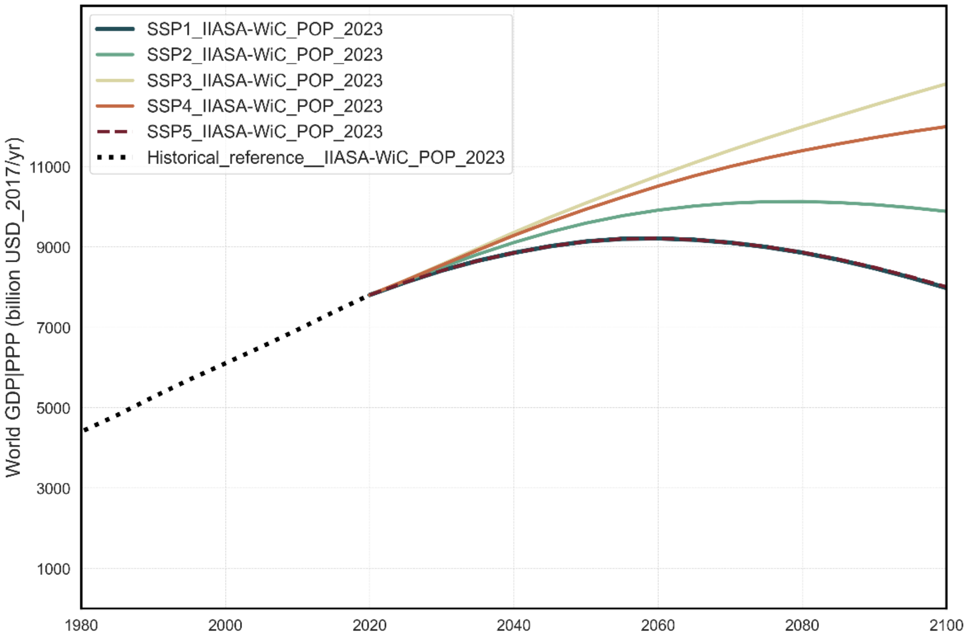

Figure B : Population in the Shared Socioeconomic Pathways version 3.1

Sources : IIASA SSP database (https://data.ece.iiasa.ac.at/ssp) based on (KC et al., 2024)

1.3. GDP per capita from IIASA SSP database

The Figure C shows the global GDP per capita trends of SSPs up to 2100.

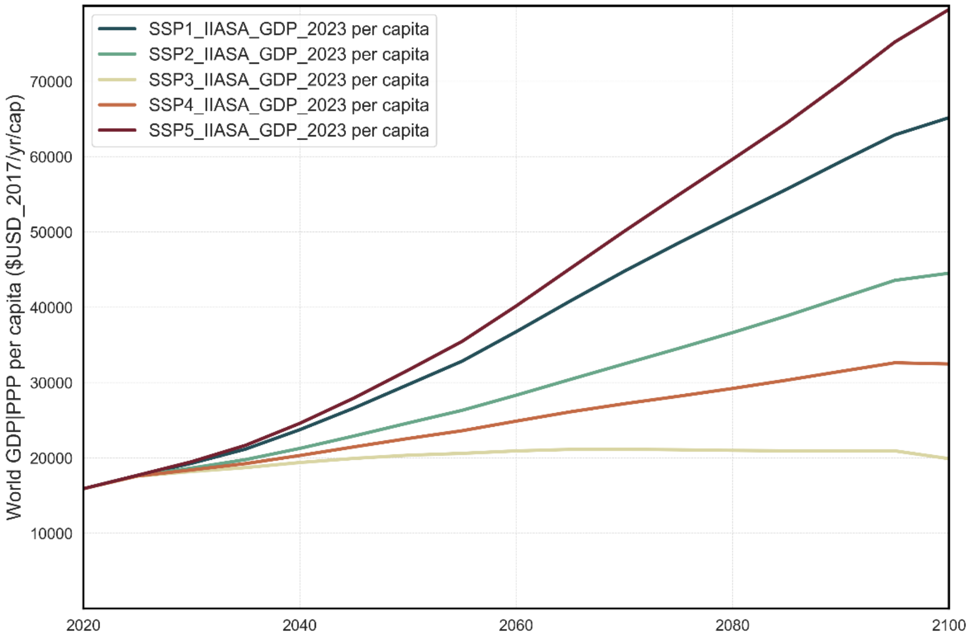

Figure C : GDP per capita in the Shared Socioeconomic Pathways version 3.1

Sources : IIASA SSP database (https://data.ece.iiasa.ac.at/ssp) based on (KC et al., 2024) & (Crespo Cuaresma, 2017)

1.4. Technologies, subsectors and aggregated sectors in DyMEMDS

Technologies and sub-sectors are represented in Table A only if copper consumption is non-zero.

Building
Building

Transport	
LV-ICV	Battery PHEV
HV-ICV	Battery EV
LV-Hyb	Battery Hyb
LV-PHEV	Intercity Elec
LV-BEV	High Speed
HV-BEV	Intercity Fossil
HV-PHEV	Vessel
Aircraft	

Other equipment	
TV	Battery Mobile
Fridge	Battery Notebook
Washing Machine	Note Book
Mobile	Battery Tablet
Dish Washer	Tablet
	Diverse equipment

Industry	
Gas pipelines	Oil Elec
Wells	Bio Waste Ocean Geothermy Elec
Oil pipelines	Hydro
Oil tankers	CSP
Oil Tanks	Geotherm
LNG plants	Wind OffS
Wind	Wind OnS
Coal Elec	Engineering Mechanic
PV	Military
Gas Elec	Chemistry Production
Nuclear	Other industrial sectors

Infrastructure	
Elec Transport	Wells
Communication	Oil pipelines
Rail Intercity Elec	Oil tankers
Rail Highspeed	Oil Tanks
Rail Intercity Fossil	LNG plants
Gas pipelines	

Table A : Technologies and sub-sectors modelled in DyMEMDS, aggregated by sector

2. ICSG database description

The International Copper Study Group (ICSG) is an independent intergovernmental organisation. One of its missions is to provide data and statistics about the copper industry (ICSG, 2024b). We used data from an ICSG database called "*Directory of Copper Mines, Smelters and Refineries - Capacities*" for this study (ICSG, 2022). Capacities represent the maximum industrial flow potential that a mine site can provide annually. This flow is limited by the amount of copper in the deposit and the industrial capacity (i.e., mining method and processing infrastructure) to process copper ore. The ICSG estimates the global capacity utilisation rate each year, which is the ratio of production to capacity. This rate exceeds 80% annually and stood at 81% in 2023 (ICSG, 2024a).

2.1. ICSG database description

The ICSG database provides information about mines according to their status (exploration, feasibility, developing, operating, closed). The database includes the following details described in Table B.

Category	*Description*
Country	name
Mine	name
Operator/Owner(s)	name and capital own rate
Process	concentrates, solvent extraction and electrowinning (SX-EW)
Status	operating, developing, feasibility, exploration, closed
Type	open pit, underground
Start Up	date
Date of Closure	date
Concs. Cu %	concentration of copper in copper concentrates
Other Metals	co-products
Short Remarks	ICSG monitoring of the mine site
2020 - 2026	capacity for each year
Project Cap.	mining project capacity, if any
Expan. Cap.	mining expansion capacity, if any

Table B : Description of the copper mine site categories in the ICSG database

2.2. Mining site status

The database contains 531 operating mines, 54 mining projects under development, 163 mining projects undergoing feasibility studies, 79 mining projects in the exploration phase, and 24 closed mines. Table C summarises the initial situation regarding the number of mine sites (see Figure D) with only a closure date, only a start date, both start and closure dates, or no dates at all. The table also includes the percentage of capacities represented in each case relative to the total capacities.

	Date of closure		Date of start		Date of start & closure		None	
	N	*Cap*	*N*	*Cap*	*N*	*Cap*	*N*	*Cap*
Operating (2022)	1/531	0%	321/531	45%	168/531	52%	41/531	3%
Developing	1/54	1%	24/54	58%	5/54	6%	24/54	35%
Feasibility	0/163	0%	28/163	24%	12/163	7%	123/163	69%
Exploration	0/79	0%	0/79	0%	1/79	0%	78/79	100%

Table C : Mining site status, date of start and closure, capacities

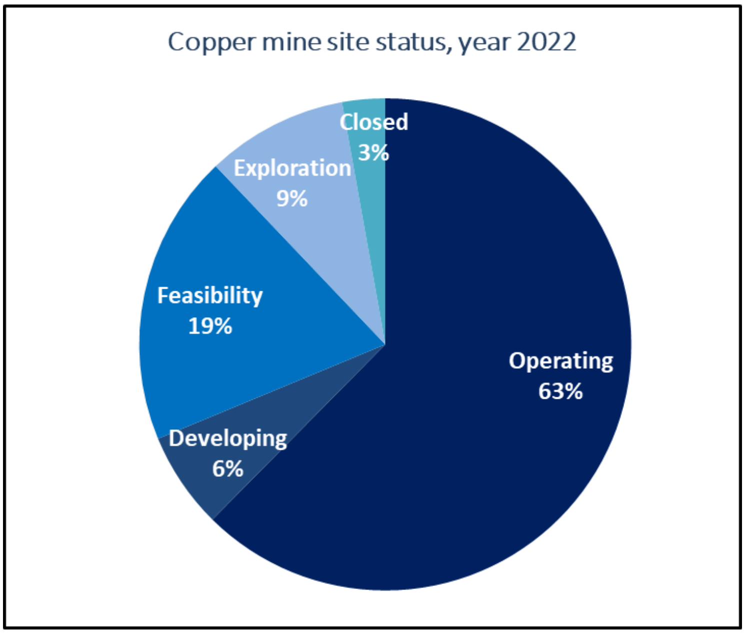

Figure D : Mine sites status, year 2022.

Source : ICSG Directory of copper mines, smelters and refineries (ICSG, 2022)

2.3. Copper mining operating capacities

In 2022, 80% of the world's copper extraction capacity will be located in 135 operating mines, representing 25% of all operating mines. These mines have extraction capacities ranging from 50 kt to 1,260 kt per year. This information is illustrated in Figure E.

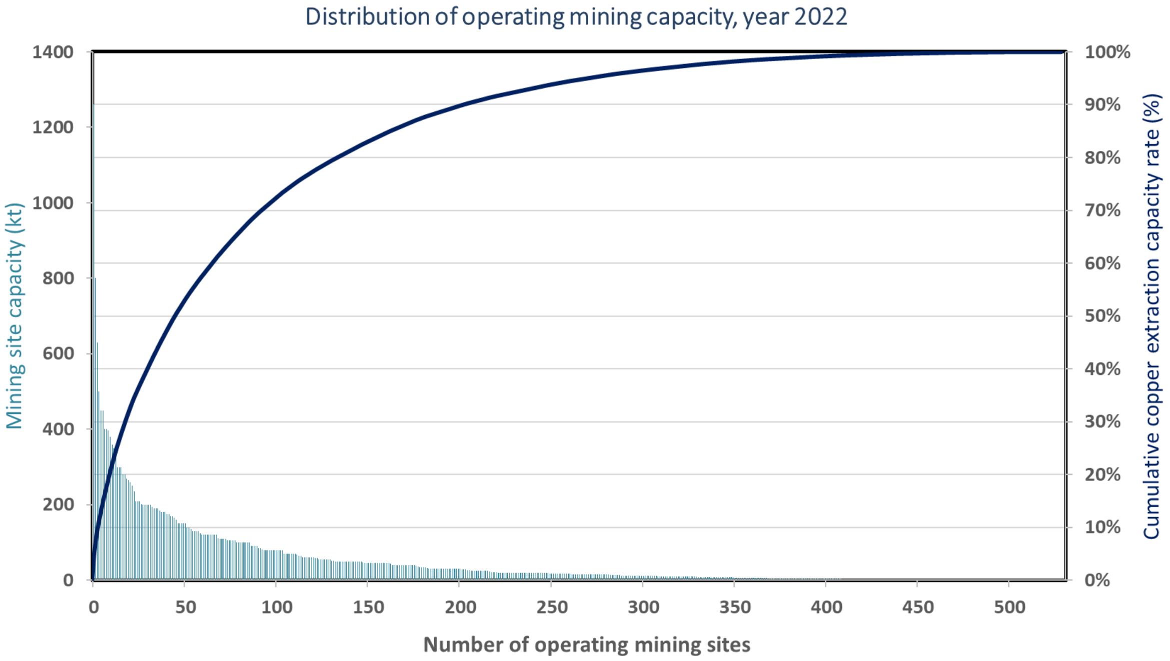

Figure E : Distribution of operating mining capacity, year 2022

Source : ICSG Directory of copper mines, smelters and refineries (ICSG, 2022)

2.4. Geographical distribution of copper mining capacity

Figure F and Figure G illustrate the geographical distribution of copper extraction capacity by country and geolocation.

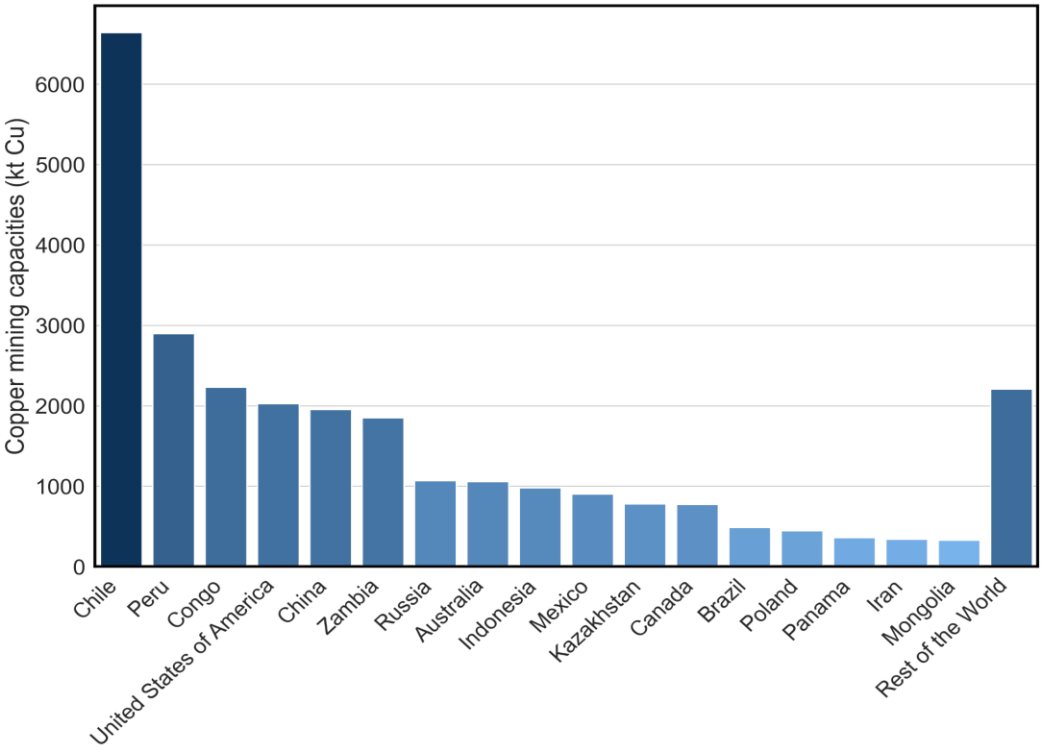

Figure F : Copper mining capacities by country, year 2022.

Source : ICSG Directory of copper mines, smelters and refineries (ICSG, 2022)

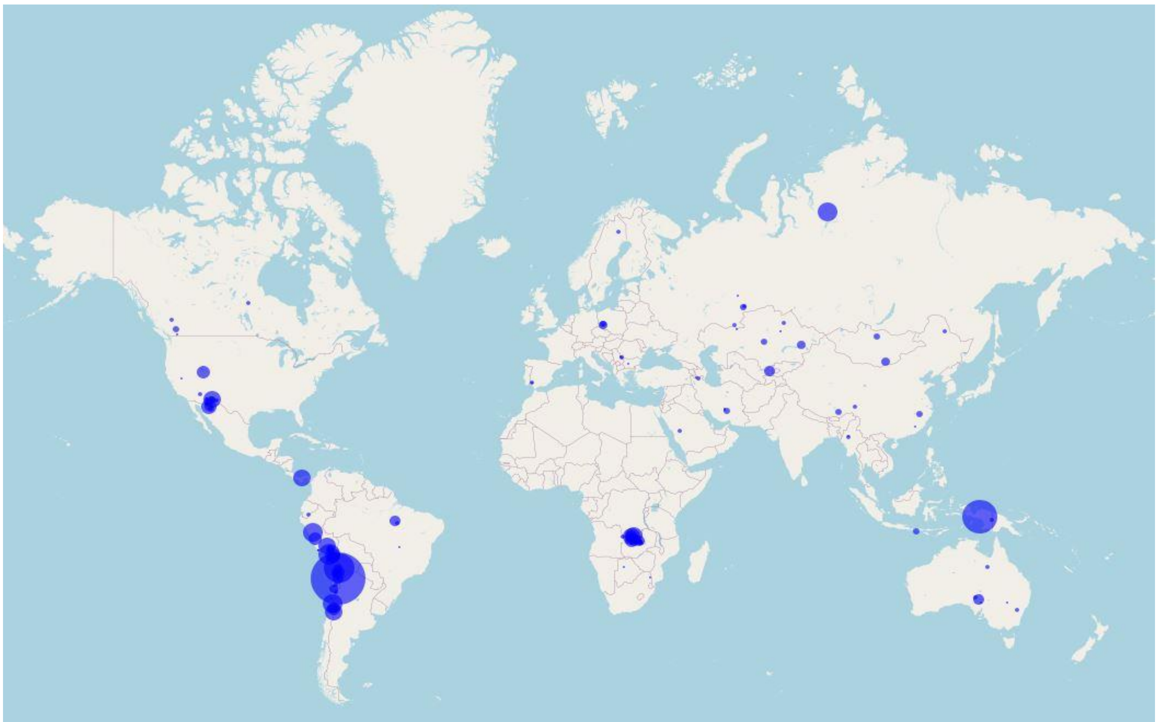

Figure G : Copper mining sites with a capacity of 50 kt or more per year in 2022.

Source: ICSG Directory of copper mines, smelters and refineries (ICSG 2022) and own analysis of GPS coordinates.

3. Forecast methodology for copper supply

In our study, a mine site is modelled as a mineral stock characterised by its capacity (tons per year), which is the maximum annual available flow, its lifetime (years), which is the duration of the operating phase, and its stock (tons), which is the quantity of extractable copper.

$$Stock = capacity \times lifetime \tag{1}$$

The ICSG database does not directly enable the projection of future copper extraction capacities. Specifically, it lacks data on two crucial categories for our study: the start date of production and the end date of production.

The methodology is detailed step by step, corresponding to a mine's life cycle : Operating in 3.1, Developing in 3.2, Expansion in 3.3, Feasibility in 3.4, Exploration in 3.5.

3.1. Operating

The initial characteristics of operating mines for the year 2022 are shown in Table D :

		Number	Capacity caracterised (kt)	Rate
Operating 2022	Date of start	321	12220	45%
	Date of start & closure	168	14219	52%
	Date of closure	1	1	0%
	None	41	880	1%

Table D : Operating mine sites in ICSG database (ICSG, 2022)

Projecting the capacities of operational mines requires knowing the lifespan of each mine. The ICSG database and grey literature provide this information for more than 50% of the operating capacities. For these mines, their capacities are projected until the closure date.

For mines without a planned closure date but with information on the site's mineral reserves, we use a methodology based on the ratio between reserves (proven and probable) and the capacities of each mine. This methodology is illustrated in Figure H.

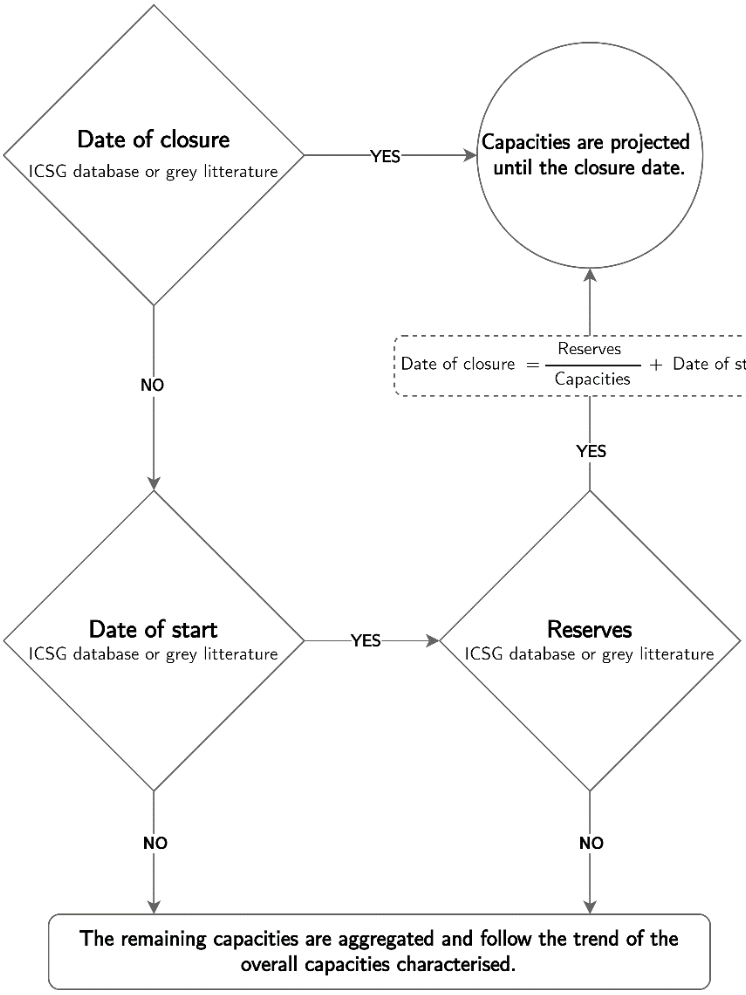

Figure H : Operating capacity methodology

It is clear that reserves are economic data based on a profitability threshold linked to the concentration of the substance of interest in the ore, extraction techniques, all costs associated with the mining project, and market price conditions. In summary, reserves correspond to the quantity of the substance of interest within identified resources that is economically, technically, and legally exploitable (U. S. Geological Survey, 1976). Nevertheless, the assumption of using proven and probable reserves seems optimistic, since it assumes that these reserves are fully profitable. It also assumes that 100% of copper ore is processed into refined primary copper, which does not correspond to the life cycle of copper. (Glöser et al., 2013).

Based on year 2022, the capacities for mine sites with closure dates indicated in the ICSG database or in grey literature (see Table E) amount to 16 536 kt (60% of operating total). The projected capacities for mine sites with closure dates calculated based on reserves amount to 4 050 kt (15% of operating total). The remaining capacities for mine sites with unidentifiable closure dates amount to 6 734 kt (25% of operating total). These capacities are projected by following the evolution of the sum of capacities with closure dates (75%) from one year to the next. For example, the overall trend between 2020 and 2021 is an increase of 5%, so we apply 5% increase to the capacities of each mine with no closure date.

Grey literature
(Andrew Issel et al., 2023a; AngloAmerican, 2024; Antamina, 2024; BHP, 2025; Carmelo Gomez Dominguez et al., 2021a, 2023a, 2024a; Chinalco, 2020; CODELCO, 2022; Congo Mines, 2009, 2022; David Gray et al., 2019a, 2020a; Glencore, 2024; GlobalData, 2022; James Young et al., 2023a, 2024a; KAZ Minerals, 2024; KGHM, 2025a, 2025b; MERDEKA COPPER GOLD, 2024; MINEX Eurasia, 2022; Mining Data Online, 2019; Mining Insight, 2023; Nornickel, 2021; NS Energy, 2020a, 2020b, 2021; OreWin, 2023a; Raúl Jacob, 2009; Rodrigo Maureira et al., 2022a; Southern Copper Corporation, 2023)

Table E : Grey literature used for operating forecast methodology

We could have used Taylor's formula to determine mine lifespan (Taylor, 1986), but it doesn't seem appropriate for our study as we are working on projects that are already in operation and whose production capacity is known. Then, to understand if the application of the mine lifespan based on reserves is robust from a modelling perspective, it is necessary to empirically compare this approach with mines whose production plans are known in the grey literature.

Figure I presents a comparison between this approach and life of mine planning presented by mining actors for a few mining sites with known production plans. We notice that in most cases, the application of this approach to reserves (proven and probable) underestimates the mine closure dates. This can be explained by the nature of mine modelling in our mining supply projections. Indeed, the assumption that production capacities and production are constant until the mine's closure overestimates the average production capacities.

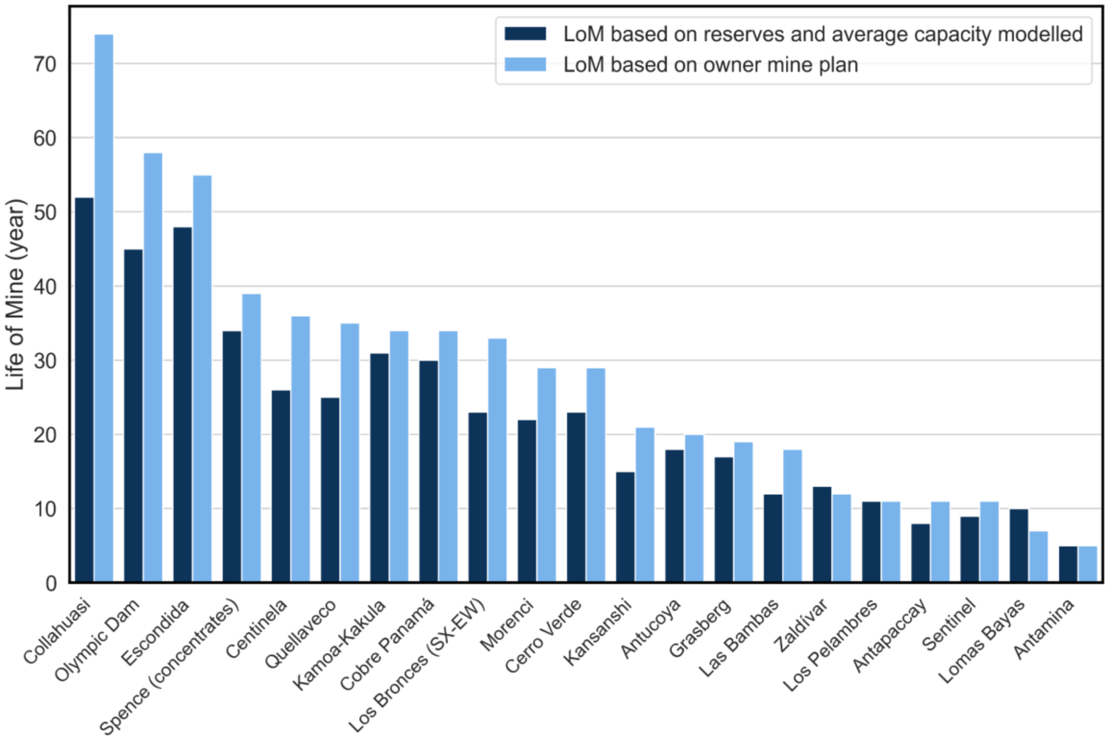

Figure I : Life of Mine comparison between owner mine plan and modelled LOM

Source : (Andrew Issel et al., 2023b; Carmelo Gomez Dominguez et al., 2021b, 2023b, 2024b; David Gray et al., 2019b, 2020b; James Young et al., 2023b, 2024b; OreWin, 2023b; Rodrigo Maureira et al., 2022b)

Notes : Antucoya and Lomas Bayas LOM are based on proven reserves only.

The solution to this issue lies in modifying the mine production plan (and therefore its capacity). Initially, the production plan was equivalent to 100% of capacity from the start date until mine closure. Consequently, the modelled ramp-up and ramp-down of operating mine capacity makes it possible to extend the mine's life by gradually increasing/reducing capacity. For non-operating projects, we assume that the ramp-up period is 3 years, compared to the 4 years described in Northey et al., (2014); Mohr, (2010), based on our analysis of data in the ICSG database. Regarding ramp-down, we observed in grey literature (see Source Figure I) that it was generally more gradual than ramp-up. We suppose that this gradual reduction in production capacity is probably due to the drop in the grade of the deposit mined for the same quantity of ore extracted, and/or to the gradual dismantling of the industrial infrastructure of the mining site with a view to its closure. Mine capacities availability rate is modelled as illustrated in Figure J, and the increments modelled are detailed in Table F.

This modelling of the production capacity plan is used for all phases of the life cycle from the moment a mine starts and/or ends production.

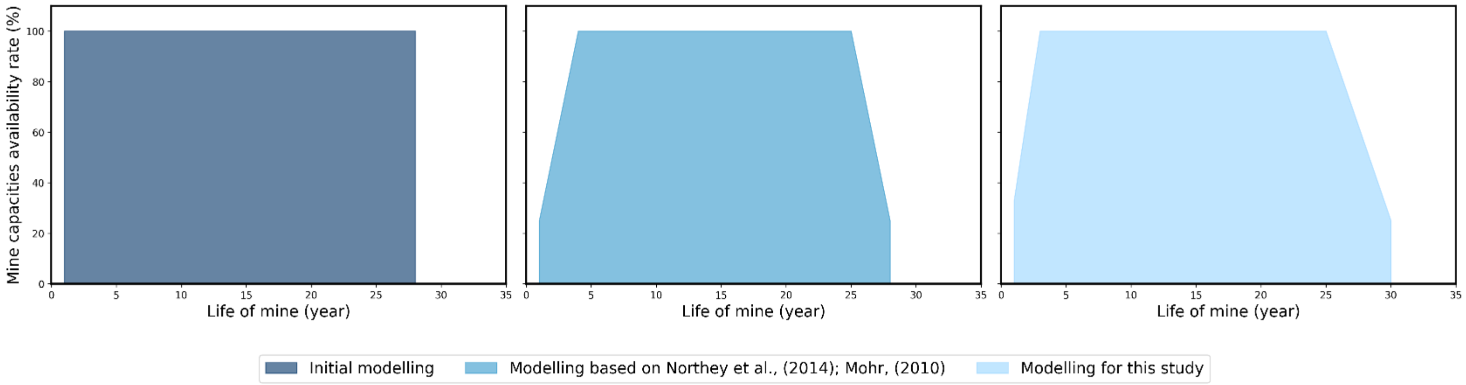

Figure J : Mine ramp-up and ramp-down modelling

Ramp-up	Start date	33%
	Start date +1	66%
	Start date +2	100%
Full capacity	…	100%
Ramp-down	Closure date -5	85%
	Closure date -4	70%
	Closure date -3	55%
	Closure date -2	40%
	Closure date -1	25%
	Closure date	0%

Table F : Ramp-up and ramp-down increments modelled

3.2. Expansion

Expansion projects for existing mines are considered as those anticipated to start production post-2026. There are 14 such projects, as detailed in Table G. For the four projects lacking opening and closing dates in the database, we utilised proven and probable reserves to determine the lifespan of the expansion projects. (see section 3.1).

		Number	Capacity caracterised (kt)	Rate
Expansion 2022	Date of start	3	465	22%
	Date of start & closure	11	1622	78%
	Date of closure	0	0	0%
	None	0	0	0%

Table G : Expansion mine projects in ICSG database (ICSG, 2022)

3.3. Developing

The production capacities of projects under development are projected using the same methodology as that for operational mines. However, only 7% of the capacities under development are characterised by a defined mine lifespan (see Table H). The majority of mine lifespans have been determined using the method that associates reserves with capacities, as previously described in 3.1. Some projects under development are intentionally excluded from projections due to suspension or significant opposition arising from social, environmental, or political concerns. These sites represent nearly 16% of all projects under development.

		Number	Capacity caracterised (kt)	Rate
Developing 2022	Date of start	24	898	58%
	Date of start & closure	50	89	6%
	Date of closure	1	10	1%
	None	24	545	35%

Table H : Developing mine projects in ICSG database (ICSG, 2022)

3.4. Feasibility

Projects capacity under feasibility studies are largely uncharacterized by either a production start date or a closure date (see Table I). This aligns with the fact that feasibility studies lead to a production plan and validate or invalidate the exploitation of a deposit.

		Number	Capacity caracterised (kt)	Rate
Feasibility 2022	Date of start	28	2738	24%
	Date of start & closure	12	736	7%
	Date of closure	0	0	0%
	None	123	7788	69%

Table I : Mine projects in feasibility study in ICSG database (ICSG, 2022)

For the limited number of sites with known production plans in the ICSG database or grey literature, capacities are projected until the closure date. For projects with a known production start date, the methodology utilising reserves determines the operational lifespan of the future mining site.

For sites with known capacities but lacking reserve information, we project the opening of capacities using the function $C_r(x)$ described in section 3.5.

For projects under feasibility studies that have not yet been characterised in terms of production capacity, we assign an average capacity of 83 kt, reflecting the known production capacities of all sites in the feasibility study.

The parameters of the $C_r(x)$ differ for feasibility studies compared to exploration projects, as feasibility study projects have a higher probability of resulting in operational mines. Additionally, since the feasibility study follows the exploration phase, the time between the feasibility study and the start of production is reduced.

We assume that all projects with at least a specified production start date will become operational mining sites. However, we introduce three cases (low optimism case, middle optimism case, high optimism case) that reflect variations in the parameters of the function $C_r(x)$ (see Table J and Figure K).

These cases aim to progressively increase the operationalisation of sites currently in feasibility studies or exploration deposits.

	H	k	x_0	a	Start year
low_optimism_case	0.75	0.20	18	0	2027
middle_ optimism_case	0.85	0.28	13	0	2027
high_ optimism_case	0.95	0.38	10	0	2027

Table J : Feasibility parameters for $C_r(x)$ function

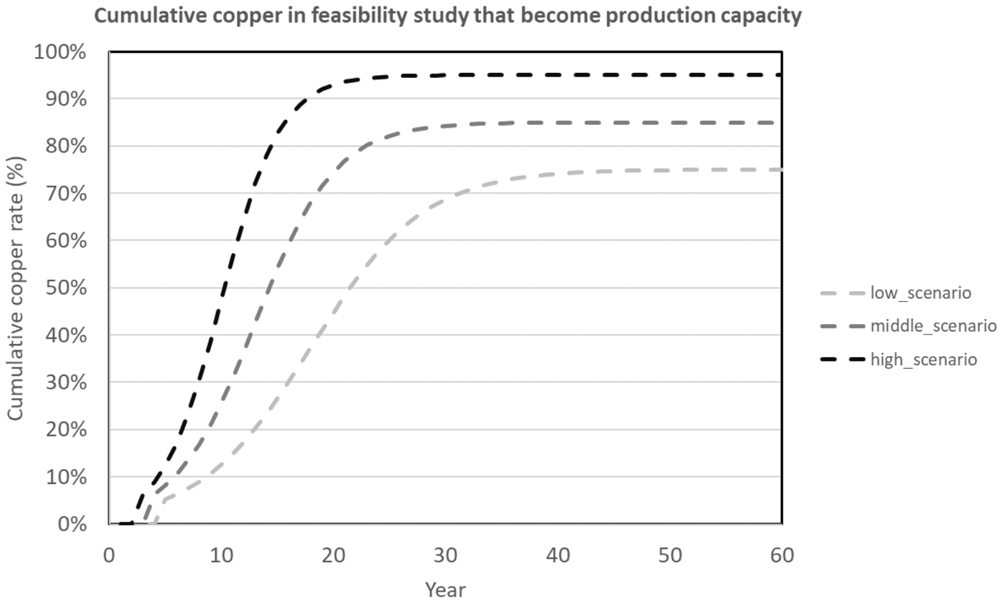

Figure K : Cumulative copper in feasibility study that become production capacity

3.5. Exploration

The ICSG data on exploration projects are deficient in terms of the start and end dates of the mine's production phase, as well as its capacity (see Table K). This deficiency is consistent with the observed average delay of 16.8 years between the discovery of a deposit and the start of production (IEA, 2021; Paul Manalo, 2024; Schodde, 2017). Across all commodities, the delay between discovery and development has steadily decreased from 1950 to 2016. However, it is plausible that future deposits may encounter longer delays.

Between 1950 and 2016, approximately 37% of discovered copper deposits were developed into mines. When considering the copper content within these deposits, the conversion rate is estimated to be around 54%. This higher conversion rate reflects the increased likelihood of larger deposits, in terms of copper content, being developed into operational mines (Schodde, 2017).

		Number	Capacity caracterised (kt)	Rate
Exploration 2022	Date of start	0	0	0%
	Date of start & closure	1	0	0%
	Date of closure	0	0	0%
	None	78	245	100%

Table K : Mine projects in exploration study in ICSG database (ICSG, 2022)

The exploration projects database catalogues 79 exploration projects. To estimate the production capacities of mines resulting from these exploration projects, the following approach is explained. Given that not all exploration projects lead to a mine, it is necessary to establish a function $C_r(x)$ representing the cumulative conversion rate of copper contained in discovered deposits leading to mine development. This function is modelled using a logistic curve that mirrors historical trends, as analysed by *MinEx Consulting* (Schodde 2017). Two key parameters are used to build this function: the maximum cumulative conversion rate and the conversion speed.

Historically, the performance of the mining industry appears to have declined in recent years, with fewer discoveries being converted into operational mines and longer conversion times (Schodde 2017). The assumptions regarding the exploration variables of the function $C_r(x)$ are presented in Table L. These assumptions may seem optimistic in light of the mining industry's historical performance trends. They are distributed according to the previously described cases (low optimism case, middle optimism case, high optimism case).

$$C_r(x) = \frac{H}{1 + e^{-k((x+a)-x_0)}} \tag{2}$$

H : maximum cumulative conversion rate

k : shape parameter, defines the conversion speed

x_0 : defines the year x in which $\frac{H}{2}$ is reached

a : adjustment parameter

	H	k	x_0	a	N	A	**Start year**
low_ optimism_case	0.50	0.20	21	0	79	81	2031
middle_ optimism_case	0.65	0.22	19	2	79	81	2030
high_ optimism_case	0.80	0.32	12	0	79	81	2029

Table L : Exploration parameters for $C_r(x)$ function

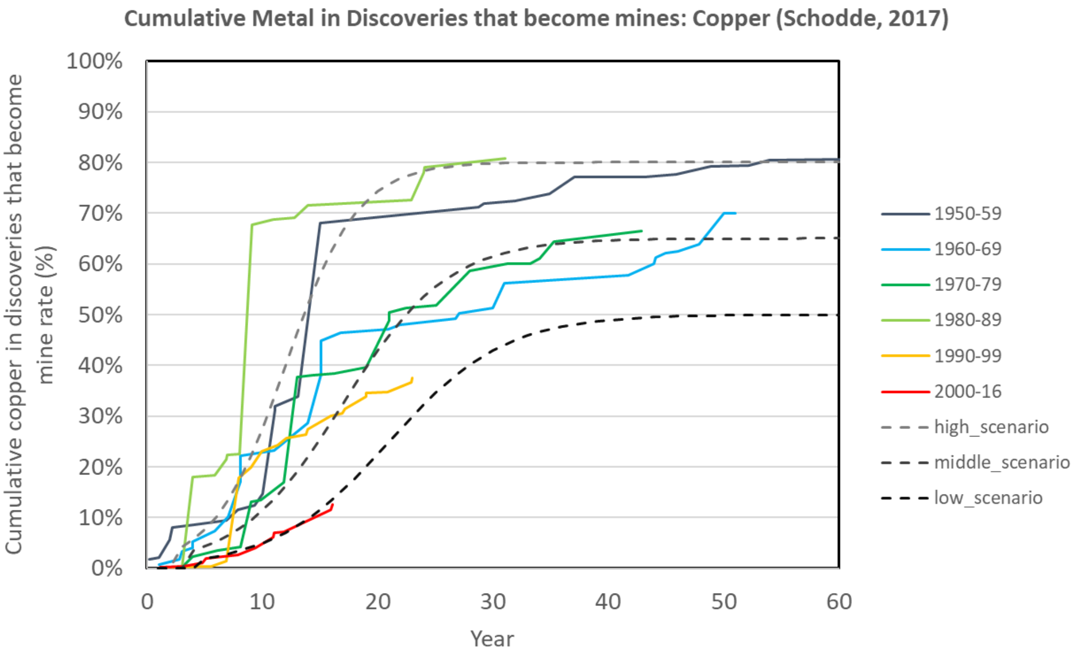

Figure L : Cumulative Metal in Discoveries that become mines: copper

(All Discoveries in the World >= Moderate in size (deposit >= 1 Mt Cu)) Reproduced from (Schodde, 2017)) with Graph Grabber 2.0 software. Caution: Not all of the available resource will be recovered from a given mine

The ICSG database does not provide information on the capacities of future mines resulting from exploration projects. Therefore, it is necessary to make an assumption regarding these capacities. We assume that the capacities of these future mines will be equivalent to the average mine operating in 2022. We calculate the average capacities (81 kt) of operating sites with a production capacity greater than 10 kt per year. This constitutes an optimistic assumption regarding future capacities; however, it is consistent with the fact that the largest deposits (and thus the mines with higher production capacities) have a higher conversion rate to operational mines than smaller deposits. To deploy these new capacities, we utilise the previously described function $C_r(x)$ by applying the following equation:

$$E(x) = C_r(x) \cdot N \cdot A \tag{3}$$

$E(x)$: function corresponding to the deployment of capacities from exploration projects

N : number of exploration projects in progress (N=79)

A : average capacity of operating mines (≥ 10 kt) in 2022 (A=81)

An uncertainty persists regarding the discoveries of deposits that may occur between 2023 and 2050. These potential discoveries are not accounted for in our analysis, which constitutes a limitation of the methodology. Nevertheless, the rate of new deposit discoveries has significantly slowed in recent years, as illustrated by Figure N and (Guj & Schodde, 2025; Schodde, 2017).

4. Results & Discussion

4.1. Primary copper capacity projections by country, 2020 – 2050

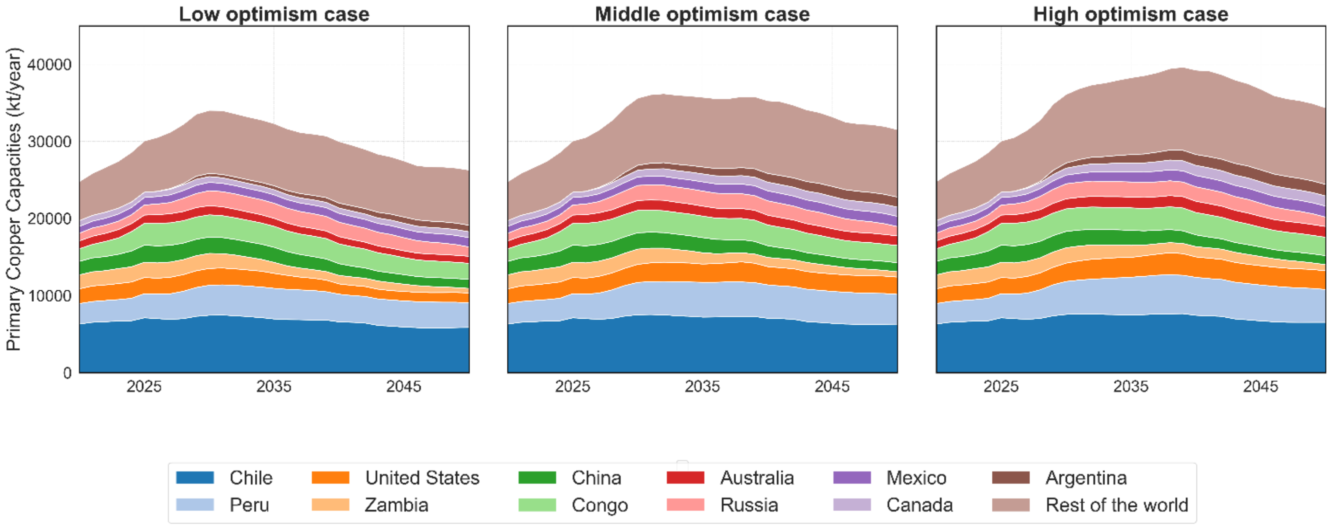

Figure M : Primary copper capacity projections by country, 2020 – 2050

4.2. Number of discoveries

Figure N illustrates the decline in the number of major discoveries (> 500 kt of copper in reserves, resources, and past production) since 2007.

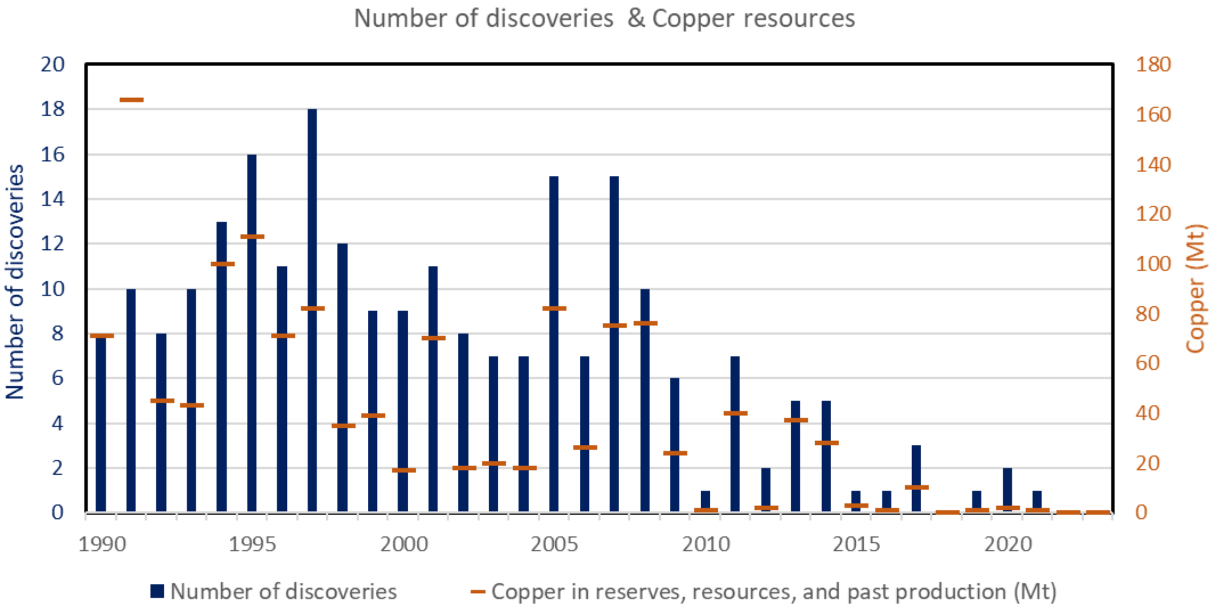

Figure N : Number of discoveries and Copper in reserves, resources, and past production

Source: S&P Global Market Intelligence (DeCoff, 2024)

4.3. Copper market price & Exploration Budget

Figure O indicates that the overall exploration budget appears to correlate with fluctuations in the market price of copper. However, the current copper exploration budget does not reach the levels observed in the 2010s, despite the market price of copper being comparable.

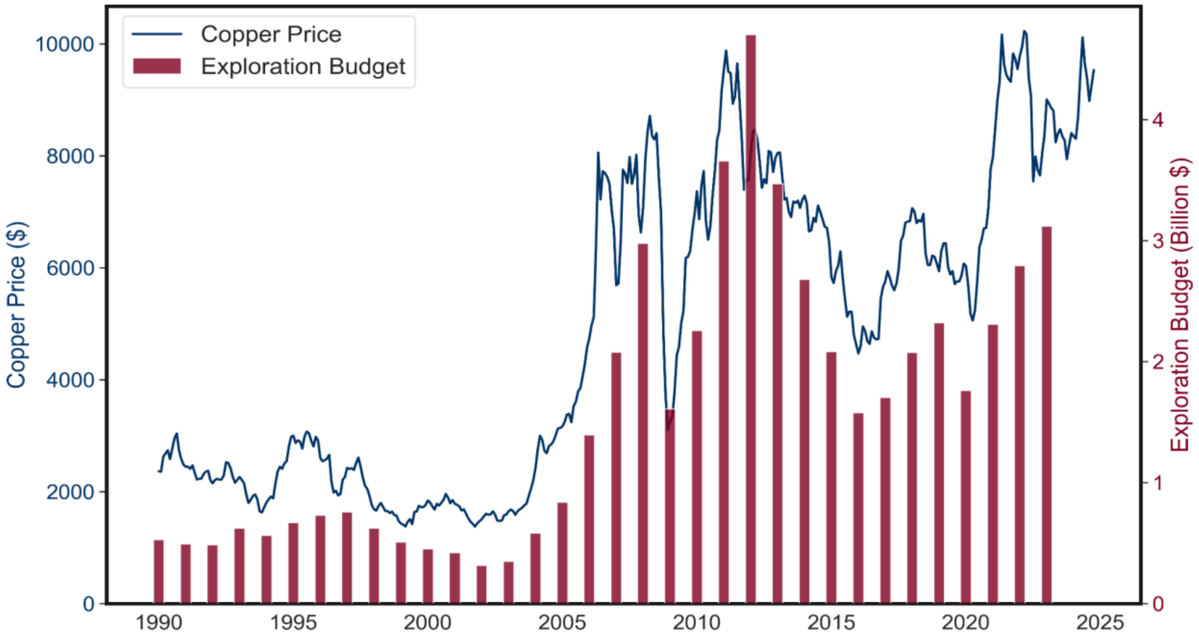

Figure O : Copper price and Copper exploration budget

Source: S&P Global Market Intelligence (DeCoff, 2024) and International Monetary Fund

4.4. Primary copper requirement scenarios comparison

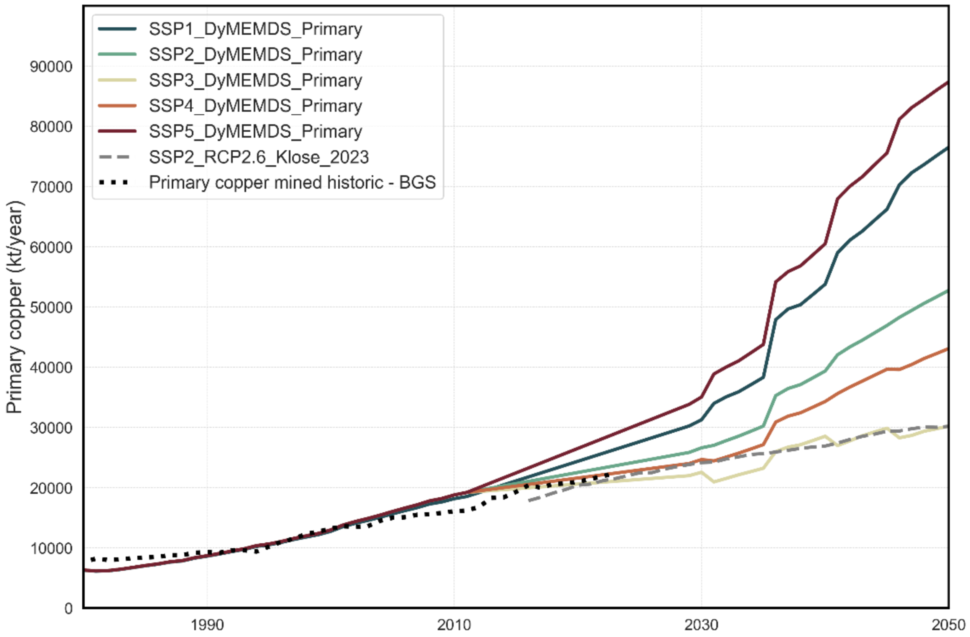

Figure P : Primary copper requirement scenarios comparison with historic (British Geologic Survey) and Klose & Pauliuk

Sources : (Klose & Pauliuk, 2023)

4.5. Copper requirements (primary + recycling), by sector

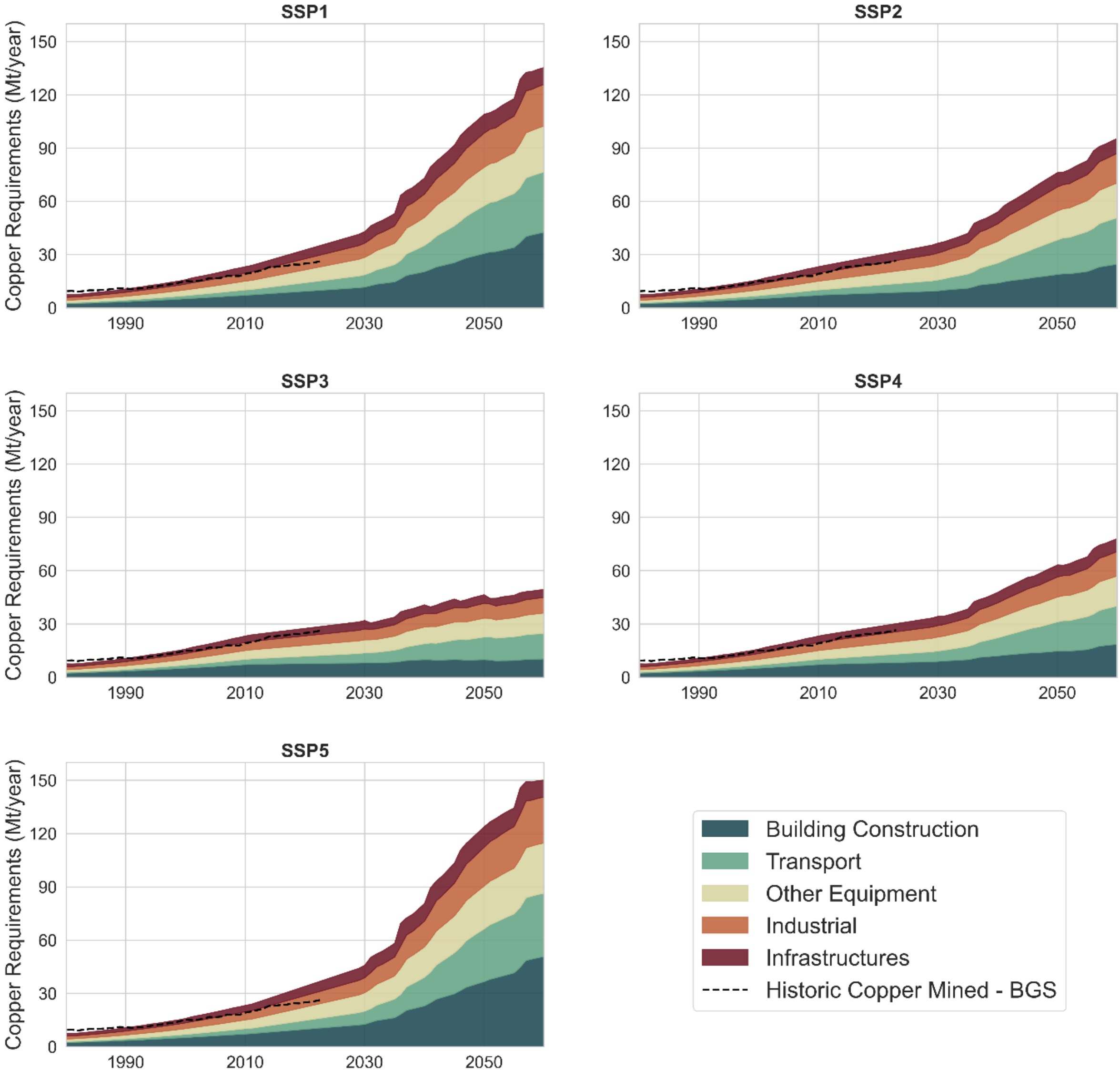

Figure Q : Copper requirements (primary + recycling), by sector

4.6. Copper requirements from recycling, by sector

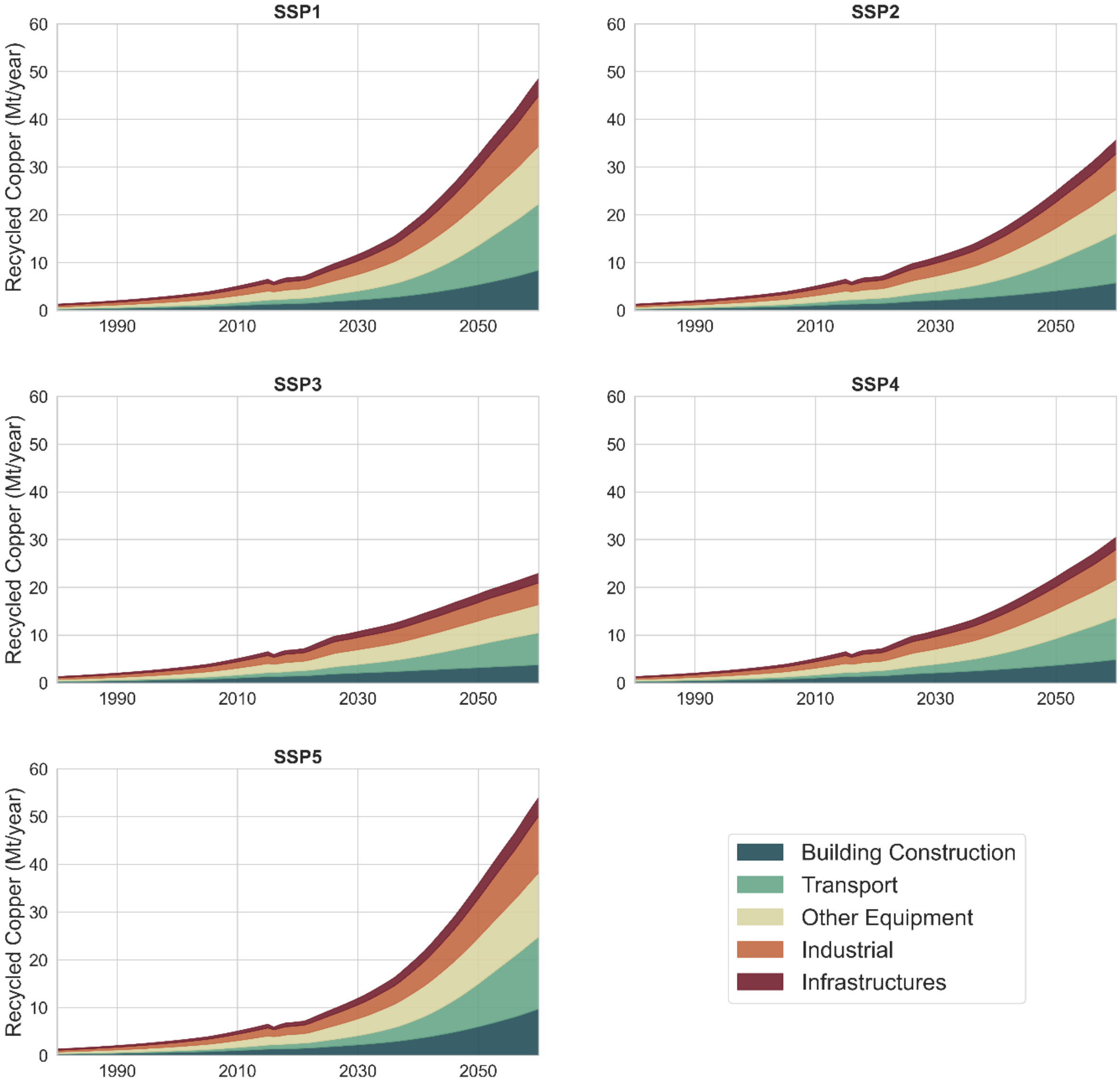

Figure R : Copper requirements from recycling, by sector

4.7. Copper requirement rates by sector

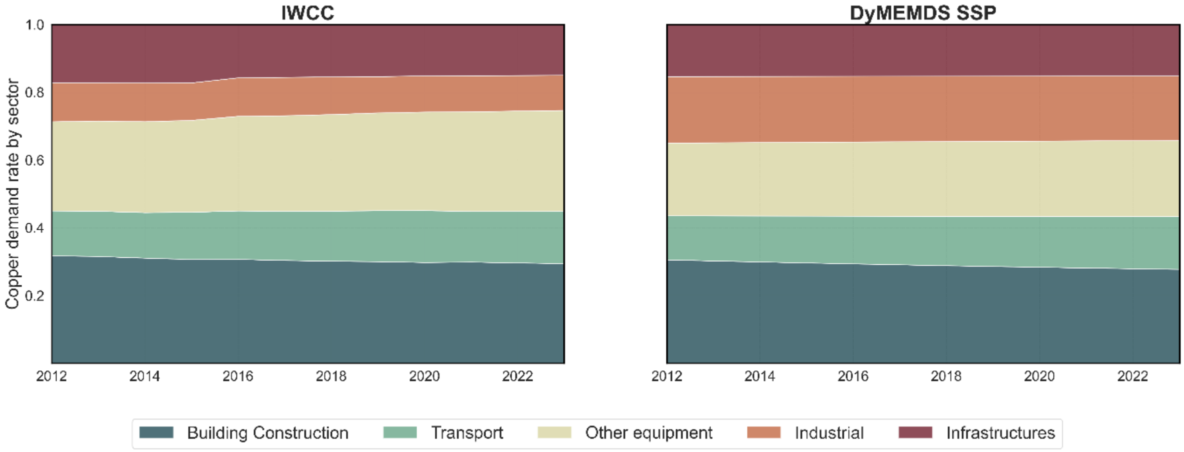

Figure S : Copper requirement rates by sector: comparing IWCC end-use sector data (IWCC, 2024) and DyMEMDS aggregated sector data

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