Toward sustainable reprocessing and valorization of sulfidic copper tailings: scenarios and prospective LCA

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Abstract

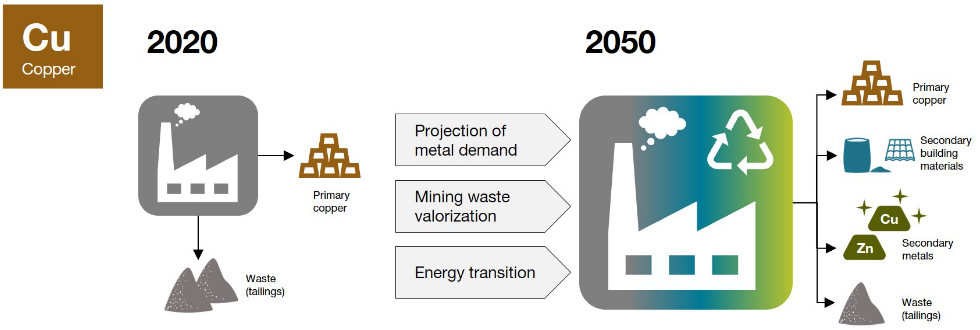
There has been increasing attention recently to reprocessing of mining waste, which aims to recover potentially valuable materials such as metals and other byproducts from untapped resources. Mining waste valorization may offer environmental advantages over traditional make-waste-dispose approaches. However, a quantitative environmental assessment for large-scale reprocessing, accounting for future trends and a broad set of environmental indicators, is still lacking. This article assesses the life cycle impacts and resource recovery potential associated with alternative waste management through mine tailings reprocessing at a regional scale. Sulfidic copper tailings in the EU were selected as a case study. We perform prospective life cycle assessments of future reprocessing scenarios by considering emerging resource recovery technologies, market supply & demand forecasts, and energy system changes. We find that some reprocessing and valorization technologies in future scenarios may have reduction potentials for multiple impact indicators. However, results for indicators such as climate change and energy-related impacts suggest that specific scenarios perform sub-optimally due to energy/resource-intensive processes. The environmental performance of reprocessing of tailings is influenced by technology routes, secondary material market penetration, and choices of displaced products. The trade-off between climate change and energy related impacts, on the one hand, and toxicity impacts, on the other hand, requires critical appraisal by decision makers when promoting alternative tailings reprocessing. Implementing value recovery strategies for building material production, can save up to 3 Mt CO_2-eq in 2050 compared to business as usual, helping the copper sector mitigate climate impacts. Additional climate mitigation efforts in demand-side management are needed though to achieve the 1.5 °C climate target. This work provides a scientific basis for decision-making toward more sustainable reprocessing and valorization of sulfidic tailings.

Keywords: Mine waste, resource recovery, circular economy, life cycle assessment, scenario analysis

Highlights

- Environmental impacts of copper tailings reprocessing in the EU are quantified.
- Future scenario narratives are leveraged to create prospective life cycle assessment models.
- Copper tailings reprocessing can mitigate GHG emissions and toxicity impacts in 2050.
- Tailings reprocessing can supply up to 2% of future European copper demand.
- Tradeoffs exist between climate change and ecotoxicity impacts for different reprocessing scenarios.

Graphical abstract



1 Introduction

The demand to solve waste accumulation problems and to supply resources sustainably have accelerated progress in emerging value recovery technologies (Rankin, 2017; Shaw et al., 2013). The mining sector is no exception. Among the most environmentally threatening waste problems is the disposal of mine tailings. When handled poorly, tailings can be the precursor of acid mine drainage, posing toxic contamination to the surroundings, even long after mines have ceased operations (Lottermoser, 2010). Currently, management options rely mostly on engineered storage through landfilling or backfilling (Kalisz et al., 2022). In the case of storage facilities, there are structural risks associated with long-term durability. Failures to manage such integrity-related risks may lead to dam collapses and environmental catastrophes (Schoenberger, 2016). Approximately 8 billion tonnes of tailings are generated annually, 46% of which comes from copper production, according to the latest estimates in the Global Tailings Review (Mudd and Boger, 2013; Oberle et al., 2020). These figures are supposed to grow as more minerals are consumed worldwide to support growth trends in emerging regions (Elshkaki et al., 2018; Herrington, 2021). Moreover, low-carbon power production such as solar, wind, and tidal, requires metals – a large fraction of which is fulfilled with primary mining (Lee et al., 2020; Valero et al., 2018; Vidal et al., 2013). Consequently, safe and sustainable solutions must be found for large quantities of mine tailings.

Many researchers and practitioners have been looking for improved management options with better environmental, social, and economic outcomes. With the advantages of gaining access to secondary materials and reducing waste volume, Edraki et al. (2014) and Whitworth et al. (2022) highlight value-adding opportunities in tailings reprocessing to recover metals and minerals. According to Spooren et al. (2020), extractive waste residues, such as tailings, may contain metal concentrations that can be higher than what can be found in the range of current economic ore grades of primary ores. Recent advancements in pyro-, hydro-, bio-, and solvo-metallurgical processing for metal extraction/recovery may capitalize on these undervalued stocks and make mine waste a resource. In addition to stranded valuable metals, the leftover residues can also be processed through valorization steps. Such steps add value by transforming residues into industrial materials, avoiding landfilling (Binnemans et al., 2015). In recent years, many studies have demonstrated viable production of alternative cement and ceramics derived from tailings (Ahmed et al., 2021; Martins et al., 2021; Niu et al., 2020; Pyo et al., 2018; Veiga Simão et al., 2021). Through valorization, tailings can also be used as raw materials in the secondary production of alkali-activated polymers: low-carbon substitutes for today's emission-intensive products such as ordinary Portland cement (Bernal et al., 2016; Mabroum et al., 2020). These opportunities generate growing interest among stakeholders and manufacturers to identify technically promising resource-recovery technologies with market and sustainability potential.

In the EU, recent years have witnessed a surge in innovations and research developments that aim to secure metals with high economic importance and avoid supply disruptions (Løvik et al., 2018). Policymakers have increasingly linked the contribution of emerging mine waste management technologies to overarching initiatives such as the European Green Deal (European Commission, 2019) and the Circular Economy Action Plan (European Commission, 2020). To translate plans into tangible findings for policy support, Blengini et al. (2019) provide various estimates of the potential recovery of several minerals compared to the current demand. Based on their simplified analysis, the authors concluded that the co-production of low-volume materials of high values and high-volume bulk minerals must be performed together to make the process environmentally viable and resource efficient. This is especially the case when specific metals are found at low concentrations in the mining waste heaps or landfills. In the EU, an innovative and integrated resource recovery research project SULTAN (https://etn-sultan.eu/) investigated the valorization of sulfidic mine waste from primary mining activities. SULTAN’s core technologies include metal extraction/recovery via, e.g., microwave/chemical assisted leaching and mineral residue valorization, aiming to convert waste into various industrial materials and create environmental benefits. While the idea seems initially favorable, collecting waste materials and processing them to useful products require energy inputs and resources. This may lead to unintended consequences and failures to reduce the net environmental impacts. Therefore, the environmental benefits and impacts need to be assessed.

Life cycle assessment (LCA) is a standardized method to assess the environmental impact throughout the life cycle stages of a product/service, including raw material extraction to the disposal process (ISO, 2006). Known for its ability to identify environmental hotspots, LCA is also increasingly applied in the minerals industry (Segura-Salazar et al., 2019). LCA studies of mine tailings treatment generally find that waste reprocessing and valorization strategies tend to reduce environmental impacts in comparison to conventional tailings management, but not always (Adiansyah et al., 2017; Adrianto and Pfister, 2022; Grzesik et al., 2019; Song et al., 2017; Vargas et al., 2020). Variability in feedstock characteristics, treatment pathways, and potential secondary products will determine the net environmental performance as well as technical and economic applicability of these reprocessing and valorization options (Beylot et al., 2022). Some studies incorporate scenario modeling to build forward-looking analysis or prospective LCA. Those studies have analyzed that parameters like metal supply, technology efficiency, production routes, and background energy system may significantly influence the resulting environmental impacts (Ciacci et al., 2020; Elshkaki et al., 2018; Harpprecht et al., 2021; Kuipers et al., 2018; Rötzer and Schmidt, 2020; Van der Voet et al., 2019). No analysis has so far evaluated large-scale reprocessing of tailings through prospective LCA, accounting for the combined effects of various future scenarios.

This study aims to quantify the environmental benefits, impacts, and tradeoffs of large-scale deployments of copper tailings reprocessing and mineral valorization technologies in the EU. The prospective nature of this assessment requires scenario modeling. To assess secondary production potential in future scenarios, we estimate the available volume of secondary products and compare them with the primary demand in 2050 based on market forecasts. The anticipated environmental footprints are assessed for a multitude of indicators to detect potential environmental burden shifting. Environmental performances for different scenarios are explored by incorporating projections in the energy transition, technological improvements for the primary copper sector, and resource-recovery technologies for copper tailings.

2 Method

In this study, we develop a framework to quantify the environmental performance of tailings reprocessing and the potential replacement from the recovered products. Figure 1 gives an overview of framework elements. This covers several steps, which are explained in the following sections: (2.1) goal and scope, (2.2) scenario development, (2.3) modeling approach and data, (2.4) background inventories, (2.5) assessment of environmental benefits and impacts of the investigated scenarios, and (2.6) sensitivity analysis.

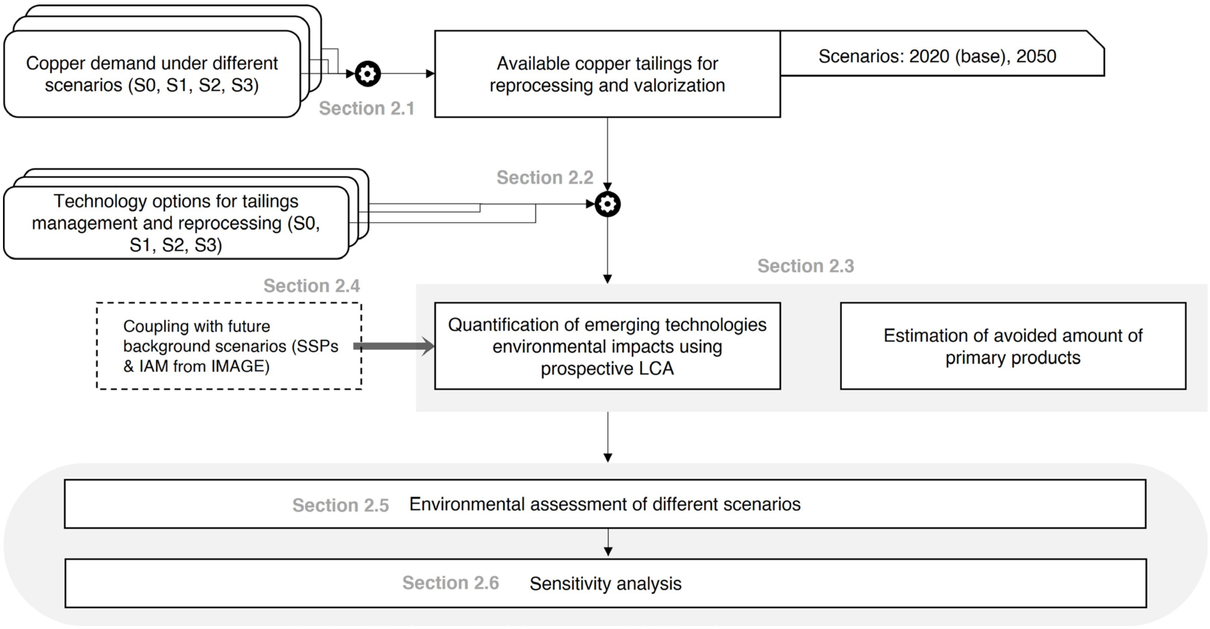


Figure 1. Workflow of the study. SSP: shared socioeconomic pathways, IAM: integrated assessment model.

2.1 Life cycle assessment: goal and scope

The goal of this study is (1) to evaluate the environmental benefits and tradeoffs between the secondary resources potential and energy/materials needed to perform the resource-recovery systems and (2) to estimate the large-scale impacts of copper tailings reprocessing in the EU. System-wide environmental analyses are performed to simulate the environmental implications of recycling/reprocessing sulfidic copper tailings. The zero-burden assumption is applied, i.e., the environmental burdens of copper tailings generation are excluded (Ekvall et al., 2007). The functional unit (FU) of this study is defined as “the treatment and management of sulfidic copper tailings arising in the EU in the year 2020/2050”. The system expansion approach is applied to assign the credits for the avoided primary productions. The substitution effects of secondary products from these alternative processes are considered in the modeling, potentially substituting the primary production of materials (Ekvall, 2020; Schrijvers et al., 2020). Specifically for offsetting products/services, a systematic selection procedure is applied based on current and future production trends (Section 2.3.4). In addition, the nature of this study involves prospective elements such as emerging recovery technologies and future energy scenarios, which encompasses changes in foreground and background systems.

2.2 Scenario development

Initially, a baseline scenario in 2020 is developed based on historical production data of copper in the EU from a combination of sources: statistics from international copper study group and commodity market intelligence platform (ICSG, 2021; S&P, 2020). Whenever available, site-specific data (i.e., volume and feedstock characteristics) for each mine site and the country is retrieved from the global sulfidic copper tailings assessment of Adrianto et al. (2022).

Future copper needs and hence, mining activities will determine the future availability of copper tailings and reprocessing potential. Three scenarios for 2050 are explored based on projected, prospective dynamic material flow analysis linked with resource scenarios of the previous studies by Ciacci et al. (2020) and Elshkaki et al. (2018). These are then coupled with the climate scenarios and future projections taken from the shared socioeconomic pathways (SSPs) with varying climate protection measures (Riahi et al., 2017).

The SSP2 "middle of the road" scenarios are selected in this study, which forecast developments similar to current trends without considerable changes in the development trajectories (O'Neill et al., 2017; van Vuuren et al., 2017). In addition to the baseline SSP2 scenario, restrictive climate policy scenarios are combined with the representative concentration pathways (RCPs) to reach stringent radiative forcing targets (Fricko et al., 2017). Projection of energy use/supply inventories and socio-economic information in the SSP2 scenarios are derived from the widely used integrated assessment models (IAMs) IMAGE (Stehfest et al., 2014). All of the SSP2 scenarios in this study assume climate mitigation in the background energy systems leading to a radiative forcing of 1.9 W/m^2 in 2100, which corresponds to 1.5°C maximum global temperature increase in 2100 relative to pre-industrial levels. For scenario 1, only conventional tailings management is applied, in line with the business-as-usual scenario. Scenario 2 relies on resource-recovery technologies with higher maturity levels and less product novelty/complexity than scenario 3, i.e., the production of industrial waste-based ceramics in scenario 2 (see section 2.3.3 for detailed comparison). These two scenarios are specifically designed to model technological innovations already described in the previous study (Adrianto and Pfister, 2022). The linking of scenarios and reconciliations of narratives result in three future scenarios, as summarized in Table 1.

Table 1. Scenario definitions.

	Tailings management options – Metal demand scenarios	**Background energy systems and equivalent SSP-RCP narratives***
Baseline scenario	S0: Business as usual (BAU) route	Current energy systems
Future scenarios	S1: BAU route – Toward equitability 2050	Climate mitigation (1.5°C scenario), in line with SSP2-RCP 1.9 W/m^2
	S2: Mineral valorization route – Toward equitability 2050	
	S3: Metal and mineral recovery route – Toward equitability 2050	

Note: *Scenarios are chosen to be as consistent as possible among each other, following the IPCC special report guidelines (IPCC, 2018). Metal demand scenarios were taken from the study of Ciacci et al. (2020).

The storylines developed for each management scenario are explained as follows:

- Business-as-usual scenario in 2020 and scenario 1 in 2050

  Copper tailings are either stored in the dam and/or backfilled. The volume of backfilled materials depends on the mine site's configuration and site information (section 2.3.2). Backfills also require additional materials and energy consumption, such as cement binder, slags, diesel, and electricity in the operational phase. In the year 2050, it is assumed that all land mining operations will install backfilling operations to manage their tailings as one of the current best practice approaches.

- Mineral valorization route, scenario 2 in 2050

  Technology improvement and successful commercialization allow building materials such as ceramics and alternative cement to be partly produced through tailings valorization. By 2050, there will be a trend toward cleaner energy mixes with less fossil resource dependence. Industry and consumers steadily accept tailings-based products in standard applications, which help substitute primary products.

- Metal and mineral recovery route, scenario 3 in 2050

  Further technology efficiency improvements and renewable energy systems are anticipated in this scenario. A notable advancement in the recycling technologies has enabled high purity metal recycling to be feasible. Emerging products such as alkali-activated binders (i.e., geopolymer as binder alternative to ordinary Portland cement) are assumed to enter the market. There is also a possibility to generate additional byproducts, such as sulfuric acid, thanks to the downstream processing of SO_2 gases.

2.3 Modeling approach and data

2.3.1 Demand projection and prospective tailings flows

Ciacci et al. (2020) estimated the potential demands for copper in the EU in 2050 using scenario analysis. These include demands for standard applications, i.e., construction, infrastructure, industry, transport & mobility, and consumer goods. To estimate total demands, copper demands for standard applications are added together with the transition demand of 1.5 Mt/year for clean energy technologies (section 1.1 of the SI). Despite this additional increase, Europe's copper mine production is expected to stay at the current level of 0.8 Mt/year, according to the metal outlook report (Gregoir and Van Acker, 2022). This domestic copper supply is used to estimate the potential volume of copper tailings. To account for copper grade declines, it is assumed that the degradation of copper ore grades follows the power regression relationship according to Crowson (2012). Copper tailings are produced from different mines, and thus it is important to fully characterize the quality and quantity of copper tailings at each site. This was performed by considering site-specific data of the generated copper tailings in the baseline/future scenarios using market data from the S&P market intelligence platform (S&P, 2020) and regionalized environmental assessment of sulfidic copper tailings (Adrianto et al., 2022). Therefore, this study only focuses on tailings assessment for active copper sites, as the site-specific tailings data from abandoned mines or closed operations are not completely available.

2.3.2 Existing copper tailings management life cycle inventory

The following section concerns the BAU and future scenario 1, as defined in section 2.2. Tailings management in Europe mainly involves two options: 1) tailings disposal/landfilling in the storage facility and 2) backfill for underground operation support (JRC, 2018). The share of landfilling to backfilling is dependent upon site configuration. This ratio for landfilling and backfilling at each site is reported in the EU best available technologies document for tailings and waste rock management. The backfilling share is approximately 10% of total tailings in 2020 (European Commission, 2009). For the year 2050, it is assumed that a higher ratio of 30% for backfilling will be applied (Garbarino et al., 2020).

For the first method via landfilling, tailings may contain heavy metals and interact with the environment, which may generate long-term emissions to the freshwater bodies. Landfilling of copper tailings is modeled using the site-specific end-of-life inventories from the study of Adrianto et al. (2022). Meanwhile, the backfilling operation datasets are derived from the primary LCA data of the actual backfill plants (Reid et al., 2009). The latter is assumed to represent copper tailings' backfilling plant unit processes. However, the resource consumption (i.e., cement, diesel, quicklime, etc.) and emissions during operation from the original study are adjusted to the capacity of copper sites under the current research. Cement stabilization of the backfilled residues was assumed to prevent any leaching emissions.

2.3.3 Emerging copper tailings valorization life cycle inventory

For the two future scenarios (scenarios 2 and 3), it is assumed that tailings management options are a function of combined technologies in the reprocessing routes. Figure 2 shows the developed process flowsheet for large-scale resource recovery efforts for copper tailings.

We employ prospective LCA for foreground and background systems (Arvidsson et al., 2018). Adrianto et al. (2022) modeled large-scale production of emerging resource recovery systems for copper tailings in foreground systems. They provided life cycle inventories based on suitable technology upscaling methods for respective technologies (section 1.2 of the SI). The background systems, such as future energy (i.e., power generation and heat) mixes, are based on the IAM IMAGE SSP2-RCP 1.9, which forecasts energy scenarios up to 2050, aligning with the SSP narratives (van Vuuren et al., 2012). The datasets for other materials and background datasets pertinent to the system in this analysis are explained in the following sections.

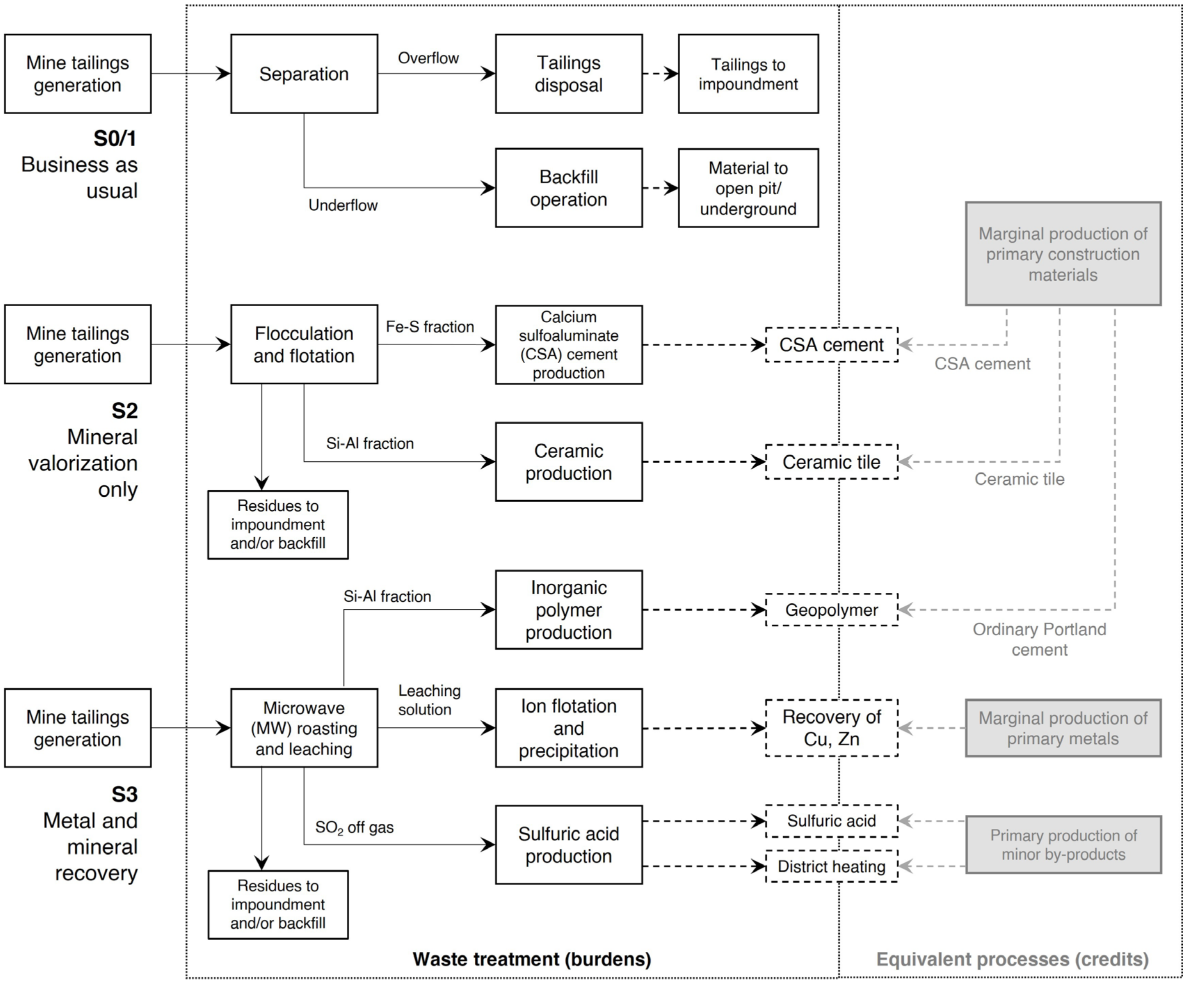


Figure 2. Management options for copper tailings applying standard disposal practices S0/S1 (Years 2020 and 2050) and two alternative resource recovery scenarios, S2 and S3 (Year 2050).

2.3.4 Marginal technologies for substituted products

As mentioned previously, this work applies a system expansion or substitution approach. Consequently, selecting the appropriate displaced products/processes is a key part of LCA studies (Vadenbo et al., 2017). We follow the identification approach of marginal data developed by Ekvall and Weidema (2004) and Weidema et al. (2009) for determining affected market processes. The approach has the advantage of determining possible marginal production without economic models and price information. Here, the long-term physical changes in supply, i.e., production quantities and growth trends of materials in different regions were taken into account (see section 5.1 in SI). There are two sub-scenarios in the environmental assessment of this study. For S0 and S1, no substitution approach is applied since the systems do not produce substituting secondary products.

Meanwhile, for the year 2050 (S2 and S3), capital investment and technological breakthroughs may play roles and are considered to reflect progress for both existing and new technologies. We made performance estimations based on forecast and material outlook for specific products, considering future-oriented environmental assessments of the construction materials (Alig et al., 2021). In the base cases, it is assumed that all secondary production routes are based in Europe, i.e., secondary production replaces primary European production (Table S9). The assumptions made and details for the marginal production technologies (referring to sensitivity in section 2.6) for each relevant process are the following:

- **Calcium sulfoaluminate (CSA) cement**. CSA cement is commercially produced for many applications where high early strength and rapid setting developments are necessary, such as patching roadways, bridge decks, airport runways, tunneling, and others. EU cement research statistics reported that small quantities are made in Europe, which can be applied according to technical approvals (ECRA and CSI, 2017). It is assumed that in 2020, 0.1% of the traditional cement market will be taken by CSA cement, and this number will grow to 15% in 2050. These values follow market penetration rates for alternative cement from holistic cement review studies (Favier et al., 2018; Habert et al., 2020).
- **Ceramic**. Most European ceramics are produced domestically in Italy, Germany, and Spain (Cerame-Unie, 2021). These internal ceramic producers are identified as the marginal production process. It is assumed that theoretical efficiency upgrades will materialize in the future, as described in the best available technology document (European Comission, 2007; Ros-Dosdá et al., 2018). Besides that, aggressive emission reduction strategies for the year 2050 are also taken from the EU ceramic association roadmaps (Cerame-Unie, 2021).

- **Ordinary Portland cement**. We rely on IEA cement technology roadmaps to define future cement production's environmental performance (IEA, 2018). If not stated in the roadmaps, technological upgrades are taken from the best available technology document (JRC, 2013) and European efficient cement manufacturing (Croezen and Korteland, 2010). Monoethanolamine (MEA) based CO_2 capture technologies with 90% absorption efficiency are considered in future cement production routes. We assume this technology is the marginal production for the European cement market in 2050, while those imported from major players in India and China are defined as alternative marginal suppliers in the sensitivity analysis.
- **Copper and zinc**. According to the IEA critical minerals special report (2021), refined copper would be globally sourced from a mix of countries. As alternative sourcing strategies, the EU imports copper mainly from Latin America, i.e., Chile and Peru (Gregoir and Van Acker, 2022). Copper production via pyrometallurgical smelting technologies remains the major production pathway worldwide. Aside from domestic production, copper produced via pyrometallurgical smelters from Chile and Peru is assumed to be the next marginal technology. For future production, energy savings potential was taken into account, assuming a reduction in electricity and fuel demand by 20% and 55%, respectively (Kuipers et al., 2018; Kulczycka et al., 2016). Zinc would be produced from mines and refineries using electrometallurgical smelting technologies (Van Genderen et al., 2016). From a recent zinc commodity report (USGS, 2022), China would remain the largest producer and is hypothetically assumed to be the marginal supplier. For future zinc production, energy demand (i.e., electricity and natural gas) are reduced by 12% according to the optimized energy consumption capacity (Qi et al., 2017).
- **Sulfuric acid and heat**. Over the last decades, a steady increase in sulfuric acid use for phosphate and sulfate fertilizers has driven its global demand (King et al., 2013a). Since

the market is distributed widely across regions, sulfuric acid production from elemental sulfur burning and heat generation (natural gas) is assumed to occur in Europe. The parameters for future sulfuric acid plants are taken from the best available technology document (European Commission, 2007).

2.4 Environmental background inventories

To facilitate the creation of prospective life cycle inventories covering future background systems, the software 'premise' is used to integrate future scenarios (Sacchi et al., 2022). This generates a systematic, complete set of prospective LCA databases containing results from the IAM IMAGE for SSP2 RCP 1.9 scenarios. The background data related to energy and material consumption in LCA are taken from Ecoinvent 3.8 database (Ecoinvent, 2022), which comply with the material types and grades applied for the study context whenever possible.

2.5 Environmental impact modeling

All scenarios are evaluated by LCA using various environmental indicators: climate change (IPCC, 2014), USEtox toxicity-related impacts (Rosenbaum et al., 2008), cumulative energy demand (Frischknecht et al., 2015), abiotic depletion potential (van Oers et al., 2002), and ReCiPe 2016 endpoint categories (Huijbregts et al., 2017). This selection of impact indicators aims to capture the most relevant impact categories when dealing with waste management and metal/mineral processing and supports comparability with other LCA studies. The environmental impact assessment is performed using the Activity Browser software (Steubing et al., 2020).

2.6 Sensitivity analysis

Sensitivity analyses are performed to test the robustness of the results and the influence of modeling choices. First, the market penetration rates of secondary products are varied from the default case, resulting in two cases: high market penetration (HM case) and worst-case assumptions (Table S7 in SI). Second, the substitution ratio of secondary materials made from tailings relative to primary materials is varied from 0.5 to the assumed default ratio 1. Ratios of substitutability might change due to differences in technical performance, perceived functionality, and market response factors, according to Vadenbo et al. (2017). This includes the effect of impurities in the products that may prevent product acceptance in the market. Third, the identified marginal productions may influence the substitution benefits for each secondary product and thus ultimately change the net environmental impacts of tailings management scenarios. In the coming decades, market shifts are expected. They might deviate from the current predicted industry trends, i.e., declining material production in the domestic market while increasing dependence on global imports of finished goods or vice versa. These would lead to changes in marginal technologies for such products and thereby define corresponding marginal suppliers outside the EU (Table S9).

3 Results and discussion

3.1 Secondary production from the reprocessing of copper tailings

Table 2 depicts how much secondary material can be produced from tailings in the EU and the volume of materials that can substitute their primary counterparts. For construction materials (i.e., ceramic and cement) across all scenarios, around 10-15% of market penetration was assumed due to market demand/supply constraints. This substantially limits the maximum scale-up potential of tailings valorization in industrial products. These effects are pronounced for ordinary Portland cement products. For illustration, less than 5% of OPC market share is assumed to be substituted by tailings-based geopolymer in 2050.

Table 2. Secondary production potential vs. material demand in EU. Volume unit in million tonnes.

Scenario	Secondary Material	Maximum possible secondary supply	Primary material substituted	Total demand forecast in 2050	Adjusted secondary demand	Fraction of secondary material uptaken in the market	Data source (for demand)
2	Ceramic tile	539	Ceramic tile	72[a]	61[i]	11%	(Cerame-Unie, 2021; Ceramic World Web, 2021)
	CSA cement	127	CSA cement	25[b]	19[ii]	15%	(Habert et al., 2020; Kelly et al., 2018)
3	Geopolymer	64	OPC cement	167[c]	6[ii]	10%	(Cembureau, 2022; IEA, 2018)
	Copper	0.1	Primary copper	4.6	0.1	Could be 100%	(Gregoir and Van Acker, 2022)
	Zinc	0.08	Primary zinc	2.9	0.08	Could be 100%	(Gregoir and Van Acker, 2022)
	Sulfuric acid	12	Sulfuric acid	25[d]	12	Could be 100%	(ChemIntel360, 2022; King et al., 2013a)

Note: a = annual growth rate of 4.1% from 2020 to 2050
b = CSA cement takes 15% of OPC demand share due to alumina availability
c = assumed stable consumption in Europe throughout the century
d = future demand is forecast through the current Europe consumption trajectory
i = assumed to be 85% of the primary demand according to the green procurement projection (European Commission, 2016; Sapir et al., 2022)
ii = market penetration and raw ingredient availability are taken from the study of Habert et al. (2020)

Secondary cement products will likely face production constraints due to the scarcity of raw ingredients (Habert et al., 2020; Scrivener et al., 2018). The limited availability of raw materials is widely recognized as the main hindrance to the rapid scale-up potentials of CSA cement (Gartner and Sui, 2018) and geopolymer (Provis, 2018). CSA cement production chain requires alumina sources such as bauxite, which competes directly with aluminum metal production. To overcome this issue, high alumina or clay substitutes suitable for CSA cement manufacturing are under investigation (Galluccio et al., 2019; Negrão et al., 2022). For a similar reason, the scale-up rates of geopolymer are also limited by the conventional alkali activators like sodium silicate in the value chain. Untapped resources of raw materials such as glass waste and red mud (Joyce et al., 2018; Mendes et al., 2021) can be exploited to produce geopolymers with similar mechanical strength to conventional ones. Therefore, large-scale production of these two types of cement depends on the availability of abundant, technically feasible, and cost-competitive alternative raw materials.

In contrast, market demand can absorb the entire volume of recovered metals in scenario 3, except for geopolymer. Increased reprocessing and recycling rates of copper tailings in the EU can mitigate dependence on imported materials or domestic virgin production and help retain the value of recovered materials within the regional economy (Figure 3). Recovering base metal from copper tailings could satisfy 2% and 3% copper and zinc total demand, equivalent to a 12% and 11% increase in domestic European copper and zinc production, respectively. Note that our study only considers on the residual minerals present in tailings produced by operational mines. The actual recovery and economic potential might be larger than estimated in this study, if copper tailings storage facilities from closed operations are included (Araya et al., 2021). The advent of novel technologies and a rising appetite for metals sourced within the EU might become a driver to develop advanced reprocessing projects for mine waste repositories (Lèbre et al., 2017; Suppes and Heuss-Aßbichler, 2021; Tunsu et al., 2019).

In addition to secondary metals and construction materials, scenario 3 has the potential to produce other byproducts, such as sulfuric acid. While sulfuric acid is not a primary purpose of reprocessing, operating pyrite roasting plants might offer additional revenue streams in the future, especially when the petroleum and natural gas industry declines due to decarbonization efforts and thus, limit the supply of elemental sulfur from sour gas (King et al., 2013b). To this end, pyrite roasting could become a promising pathway for producing sulfuric acid (Ober, 2002; Runkel and Sturm, 2009).

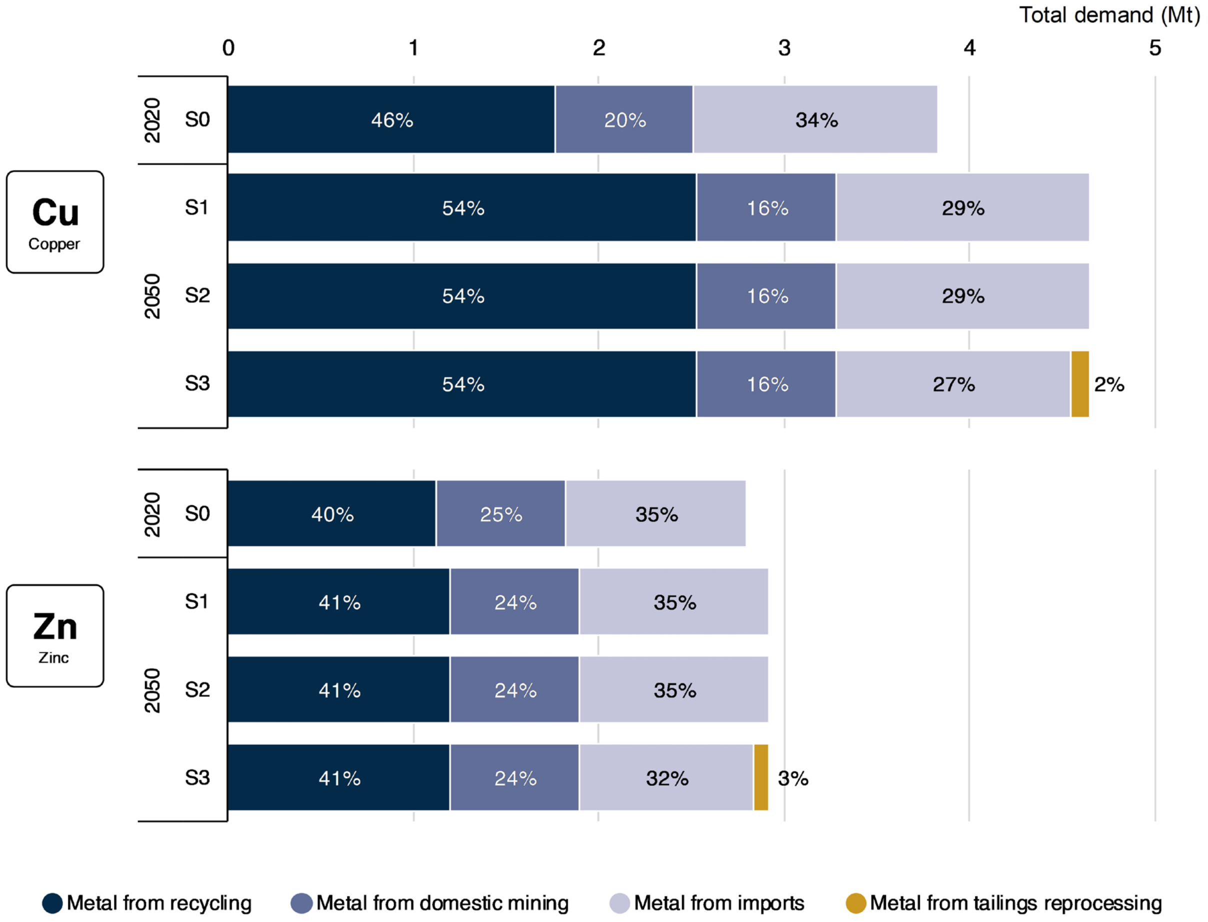


Figure 3. The share of metal supply (copper and zinc) from various sources, including domestic extraction, recycling, import, and copper tailings reprocessing. Bars' length denotes the total metal demand in current and future scenarios, adapted from other studies (Ciacci et al., 2020; Gregoir and Van Acker, 2022). Numerical details in Tables S1-S3 in the SI.

3.2 Life cycle environmental impacts: baseline and future

Figure 4 shows the environmental performances of copper tailings management in the baseline year (Scenario 0) and the future scenarios with different treatment options (Scenario 1, 2, and 3). Positive values represent the environmental burden caused by managing tailings in the facility storage and performing backfill operations. The negative values represent the environmental credits of replacing and thus avoiding impacts of manufacturing primary metals and building products. Negative overall values (black crosses) mean that the management of copper tailings has net environmental benefits and is favorable for the selected indicators.

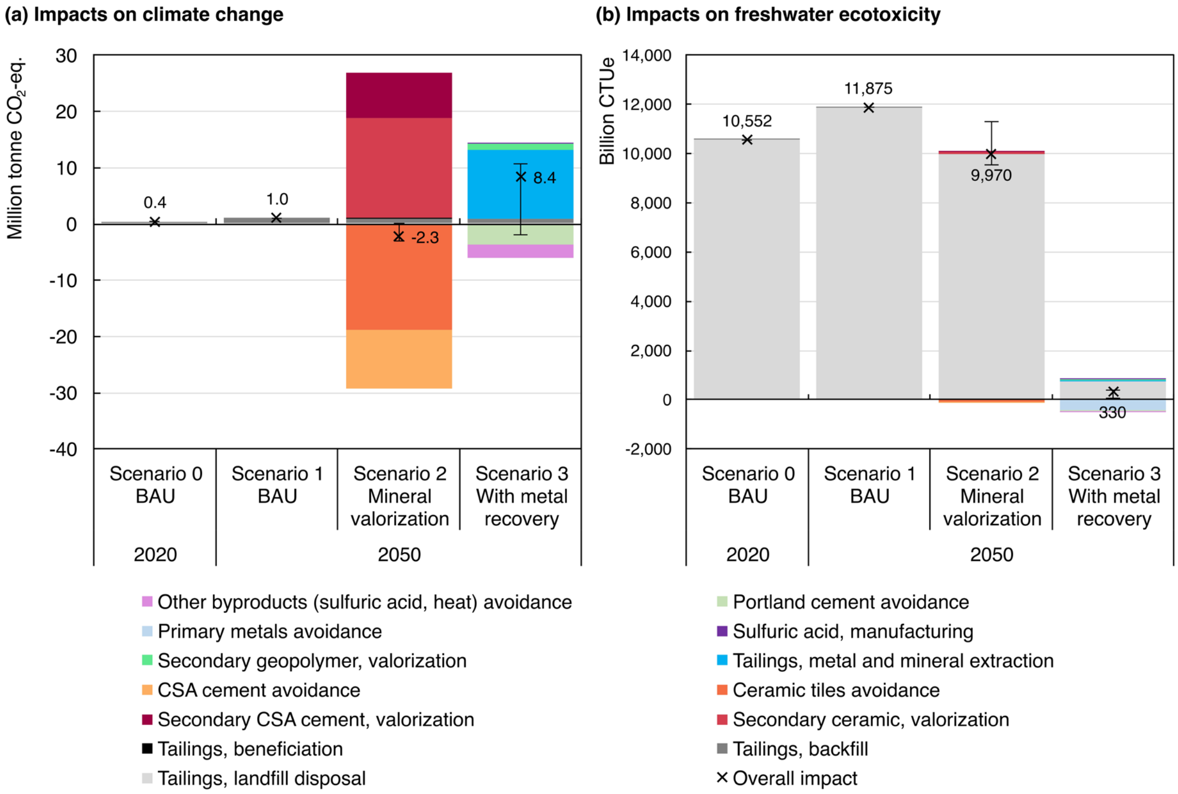


Figure 4. Prospective environmental impact from the management of copper tailings in EU under different treatment options. Two midpoint impact categories are shown: a) IPCC 2013 Climate change, b) USEtox freshwater ecotoxicity (see SI for further indicators). The high and low whiskers indicate the possible variation in product market penetration (worst case and HM case, Table S7 in SI).

We found that implementing current tailings management options (scenarios 0 and 1) would always generate net impacts across indicators. Moreover, the total impacts of scenario 1 are always higher than scenario 0, as both scenarios implement the same combination of disposal and backfill operation, but scenario 1 has higher demand of copper. Declining ore grades would contribute to the growing volume of waste from metal processing in 2050 (Calvo et al., 2016), despite relatively stable domestic copper production in Europe throughout the mid-century (Gregoir and Van Acker, 2022). In scenarios 0 and 1, freshwater ecotoxicity impacts are higher than in the other scenarios due to long-term freshwater contamination by heavy metal leaching, potentially leading to acid mine drainage. Even if European countries were not found to be an individual global hotspot for toxicity impacts caused by tailings landfilling, the sum of all impacts in the region should not be underestimated in the aggregate (Adrianto et al., 2022).

Scenario 2 offers net benefits on climate change, cumulative energy demand, and resource depletion environmental indicators. Producing secondary ceramic tiles and CSA cement (with the amount specified in Table 2) can save up to around 2 Mt CO_2 eq. in 2050. If a lower quantity of secondary materials is available in 2050 (Table S7 in SI), the resulting net benefits for all three indicators would instead turn into net impacts. Furthermore, although a reduction of ecotoxicity impacts can be expected (16% decrease from scenario 1), there are still substantial tailings disposal environmental risks that must be managed safely in the future.

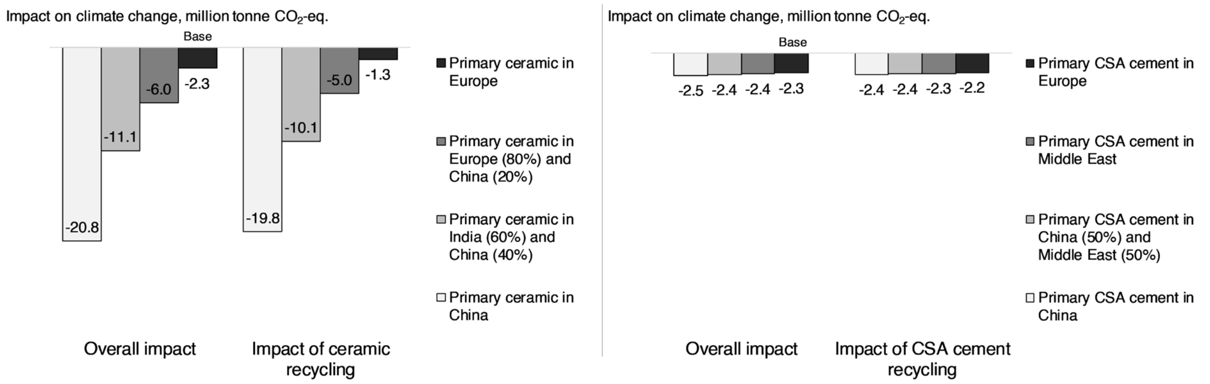
One way to minimize ecotoxicity impact potentials is by extracting the acid-generating compounds and metals from copper tailings, as applied in scenario 3. Converting pyritic compounds into other byproducts such as sulfuric acid and recovering companion metals, can significantly reduce ecotoxicity impacts. Besides the lower potential of leaching from the disposal of residues, supplemental material from tailings reprocessing may also substitute primary production, that otherwise would generate voluminous toxic waste such as tailings in the upstream metal ore processing. Gleaning metals from low-quality ores/deposits, as analyzed by Norgate and Jahanshahi (2010), comes at high resource expense, leading to burden shifts to energy-related impact indicators. In contrast to the previous study by Adrianto and Pfister (2022) that assumes unlimited demand for secondary products, this study shows that after credits from all secondary products are accounted for, a net environmental impact remains. Still, scenario 3 offers drastic reductions in ecotoxicity impacts compared to other scenarios. This advantage becomes crucial given the significant contribution of copper production to the global ecotoxicity impacts of metal resources (IRP, 2019).

The net impacts turn to net benefits under best-case assumptions for geopolymer market penetration (Figure 4, low whiskers). Therefore, GHG emissions of scenario 3 may be lowered by: 1) exploration of other metal/mineral extraction techniques to further reduce energy and resource (i.e., ceramic/cement ingredients and leaching agents) consumption during reprocessing, since the proposed processing methods in the future are close to the theoretical limits; and 2) the capability to substitute ordinary Portland cement at larger volumes domestically, or to partially sell in international markets beyond the EU boundaries.

3.3 Sensitivity analysis

The effects of modifying variables in LCA—such as the origin of substituted products and the definition of substitutability for product displacement—deserve further investigation. Our results were reproduced using different assumptions (section 5.1 of the SI). Overall net GHG footprints for scenario 2 range from -2 to -21 $MtCO_2$-eq (Figure 5A). If ceramic tiles production in China were displaced instead of Europe (base case), the overall net environmental benefits of scenario 2 would increase by almost one order of magnitude. The reason is the energy-intensive process of primary ceramics production, which in China is supplied mainly by coal-based electricity (Wang et al., 2020), while in Europe, it is electricity- and natural gas-based. While there is also potential to lower GHG emissions when displacing OPC cement without CCS in scenario 3 (Figure 5B), these measures are insufficient to entirely compensate for the high GHG emissions caused by secondary metal recovery. Primary copper production via pyro- and hydro-metallurgical routes is projected to only make a slight difference in performance as the background energy system moves toward carbon neutrality and foreground technology efficiency improves (Kuipers et al., 2018). Furthermore, with the small volume of secondary metals recovered in scenario 3, changing marginal suppliers has negligible effects on overall GHG performance.

A. Scenario 2: Mineral valorization



B. Scenario 3: With metal recovery

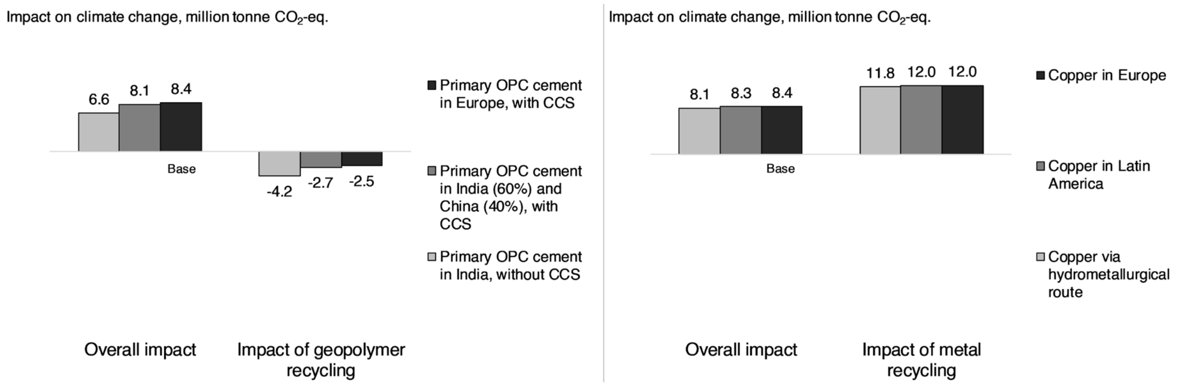


Figure 5. Change of marginal technologies for primary material production: effect on climate change impacts for scenarios 2 (top) and 3 (bottom). Overall impact refers to the total impact of all processes. In contrast, impact of recycling shows the net impact of recycling secondary products, i.e., reprocessing burdens minus credits from selected marginal production separately.

Regarding varying substitution rates for both scenarios, Figure S5 shows how sensitive the net GHG impacts are when the substitution factors for secondary products are changed simultaneously (section 5.2 of the SI). For scenario 2, having secondary ceramic and CSA cement with substitution ratios above 0.8 is crucial to keep the net GHG balance negative. For SRs < 0.5, scenario 2 would perform even worse than scenario 3, which has no GHG mitigating effects in the default case.

3.4 Contextualizing the impact of copper tailings management

One of the eminent challenges in the copper sector is to satisfy growing copper demand while meeting climate goals. As the energy system decarbonization progresses, copper production can also benefit from such a transition (Figure 6). Moreover, the trajectories of future demand under different scenarios dictate how much copper should be supplied (Ciacci et al., 2020). When alternative tailings reprocessing strategies are applied as in scenario 2, GHG emissions can be mitigated with the expected future secondary market demand. By contrast, scenario 3 does not lead to net GHG savings due to the high energy consumption for the metal extraction, as discussed in section 3.2. Yet, this is different for high market penetration rates of secondary cement (Table S7 in SI). However, even with energy efficiency improvements, decarbonization of the power sector, and improved tailings management, additional collective measures are needed to achieve the total GHG emission targets for the EU copper sector. To meet the 1.5°C decarbonization goals, additional reductions of approximately 36% (scenario 2) and 50% (scenario 3) are required to close these emissions gaps (Figure 6).

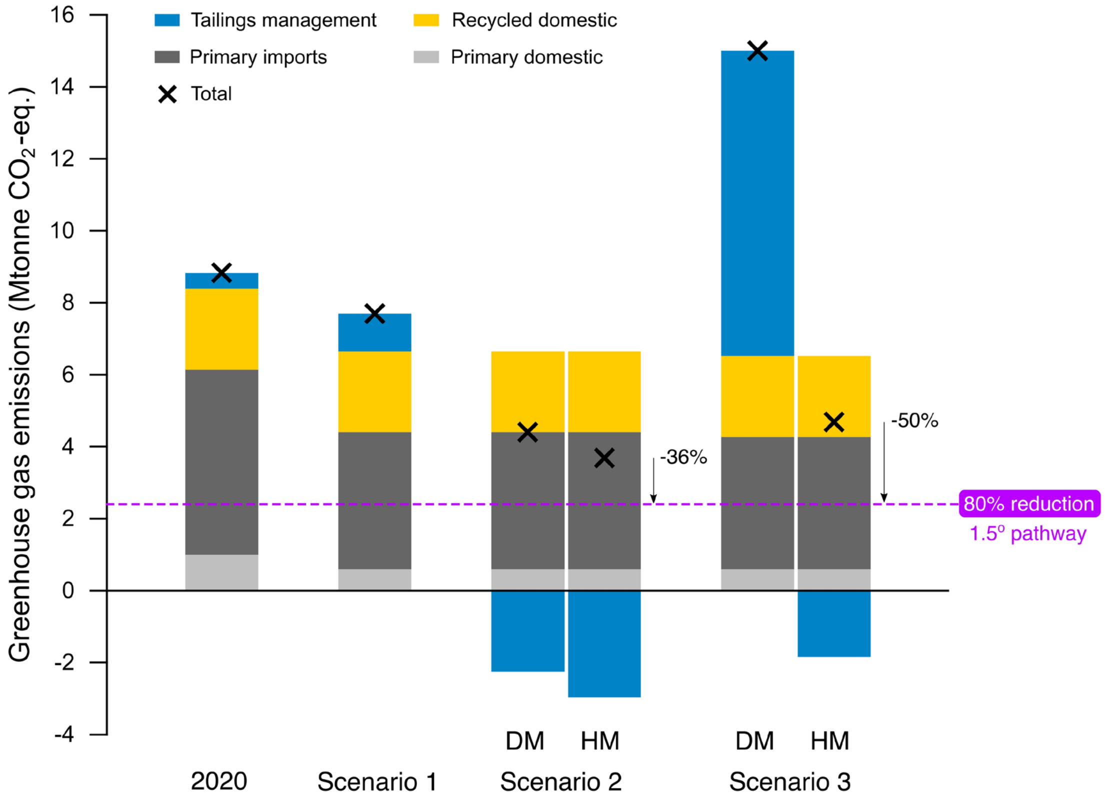


Figure 6. Estimation of greenhouse gas emissions embodied in copper demand in the EU according to different scenarios. GHG emissions with alternative tailings management and different secondary product market penetration are compared for each scenario. The dotted lines indicate the reduction of GHG emissions as required in the industry roadmaps (European Copper Institute, 2014). Consumption-based accounting is applied. Numerical details are presented in SI section 8. DM: Default market penetration rates (base case), HM: High market penetration rates (HM case).

It is crucial to note that Europe's copper emission occurs mainly outside the territorial boundary according to the consumption based GHG accounting. Consumption-based accounting for the sector, which sums both emissions occurring in the domestic economy and embedded in imports from other countries, indicates that copper imported from abroad is responsible for more than 50% of the sectoral emissions induced by EU metal consumption (Table S13). A similar finding was discussed for countries with few or no mining activities in other European countries (Mayer et al., 2019; Muller et al., 2020), calling for the roles of additional climate change mitigation measures in reducing carbon footprints beyond territorial boundaries.

For deep decarbonization in the copper sector by 2050, Watari et al. (2022) discuss the importance of multiple measures on both, production side innovations and demand side management. Given that no silver bullet exists, a diffusion of different strategies is essential to meet the emissions reduction target. Central to today's context, this includes GHG-saving copper production, electrification, and aggressive recycling. While waiting for the core technological innovations to scale on time, other key levers, such as more efficient use of copper for the same services and product lifetime extension, could narrow or even bridge the emission gaps.

Based on the scenario modeling, reprocessing copper tailings in the EU could avoid approximately 2 – 3 Mt CO2-eq. in 2050. The emission targets set by the European Commission (2018) imply a reduction of 128 Mt CO_2-eq. in 2050 for the “2.C metal industry” category (European Environment Agency, 2022). Thus, implementing system-wide reprocessing of tailings (HM case) in Europe would result in the avoidance of 1.5% for scenario 3 to 2.3% for scenario 2 of the total reduction measures in the category “2.C metal industry” (Table 3).

While these estimated GHG reduction values are uncertain, the magnitude indicates how many benefits or tradeoffs alternative waste management can generate. Most importantly, due to the transboundary nature of product displacement, the impact reduction for the two sub-scenarios in Table 3 that also account for GHG savings outside the EU, should be interpreted with caution. Although the global industry may benefit from implementing this approach regardless of location, the GHG reporting and inventory assessment for such cross-sectoral cooperation between entities must be carefully resolved to avoid double counting of GHG savings.

Table 3. Contribution of the copper tailings reprocessing to Europe's GHG reduction targets in 2050.

Years	**1990**	**2020**	**2050**	**2050, only EU production**		**2050, displacement outside EU borders**	
		S0	**S1**	**S2**	**S3**	**S2**	**S3**
Total GHG emissions, all categories[a], Mt CO_2-eq.	4,633	3,068	232	232	232	232	232
Net GHG emissions, metal industry[a], Mt CO_2-eq.	135	64	7	7	7	7	7
% reduction from 1990 levels, metal industry[b]	-	53%	95%	95%	95%	95%	95%
Reduction targets relative to 1990, all categories, Mt CO_2-eq.	-	1,565	4,401	4,401	4,401	4,401	4,401
Reduction targets relative to 1990, metal industry, Mt CO_2-eq.	-	71	128	128	128	128	128
Tailings management impacts[c], Mt CO_2-eq.	-	+0.4	+1.0	-2.3	+8.4	-21.1	+6.3
Tailings management impacts[c], Mt CO_2-eq. (HM case)	-	-	-	(-3.0)	(-2.0)	(-21.9)	(-11.2)
% tailings management impacts/reduction targets of all categories	-	+0.0%	+0.0%	-0.05%	+0.2%	-0.5%	+0.1%
% tailings management impacts/reduction targets of all categories (HM case)	-	-	-	(-0.1%)	(-0.04%)	(-0.5%)	(-0.3%)
% tailings management impacts/reduction targets of the metal industry	-	+0.6%	+0.8%	-1.8%	+6.5%	-16.4%	+4.9%
% tailings management impacts/reduction targets of the metal industry (HM case)	-	-	-	(-2.3%)	(-1.5%)	(-17.1%)	(-8.7%)

Note: For material displacement outside the EU in 2050, high-impact production from marginal sensitivity tests was chosen. HM case represents the scenario with high market penetration for secondary products. Positive (red) and negative (green) values are color-coded. More discussions can be found in the SI section 9.

[a] GHG inventory data for 1990 and 2020 from EEA (2022), covering six source and sink categories: 1. energy, 2. industrial processes, and product use, 3. agriculture, 4. land use, land use change and forestry, 5. waste, and 6. Other;

[b] Defined GHG emission targets for both business as usual and decarbonization vision from EU commission (2018), assuming percentages apply equally across categories. The targets are used to estimate GHG inventory data in 2050;

[c] Own calculation (Figure 4 and Figure 5).

The evaluated case represents one example of climate mitigation solutions through waste management. Other breakthrough technologies beyond our analysis might penetrate the market and become commercialized, amplifying the GHG reduction potential through improved energy and resource intensity. For example, various types of tailings have been regarded as promising storage for the carbonation process, enabling CO_2 capture for emissions offset (Bullock et al., 2021; Wilson et al., 2014). Such solutions should also be assessed with LCA to complement the present study.

3.5 Implications for practice

This study has implications for business activities in the copper and materials industry. Today, business opportunities and sustainability standards in the copper sector have been focusing on technological upgrades and decarbonization of the production system. One area that lacks investigation is understanding the role of waste management through a life cycle assessment combined with a metal scenario outlook. Our research shows secondary production potential by reprocessing copper tailings in the EU.

Implementation barriers include heterogeneity of material properties, economic uncertainty, fragmented legislation, and conflicting corporate cultures/values (Almeida et al., 2020; Sibanda and Broadhurst, 2018). Additionally, in the context of EU mine tailings valorization, the lack of relevant regulatory standards for waste-based materials and financial incentives represent key bottlenecks in accelerating the use of industrial byproducts over virgin building materials (Kinnunen and Kaksonen, 2019). Beyond that, additional work is critical to demonstrate the applicability of new products at the desired scale. Tight regulations might sometimes prevent scalability even when the technologies are proven. The industry must be willing to go through national approval processes with often differing political and regulatory conditions before such products can successfully enter the market (Material Economics, 2022).

Our analysis reveals tradeoffs between climate change and ecotoxicity impacts for scenarios 2 and 3. Although small GHG reductions are possible by 2050, exploring additional strategies to meet future climate ambitions is imperative to meet the Paris climate agreement. Reijnders (2021) proposed the idea of near-zero waste production of copper, making use of the geochemically scarce elements and mineral matrix considerably lost in tailings, slags, and dust during the mining and refining stages. Assessing novel metallurgical processes and improving the recoverability of these elements/minerals may open doors for additional ecological benefits.

3.6 Opportunities for future work

The material demand projection and forecast based on established scenarios and integrated assessment models are uncertain. Our results should be understood as exploratory projections rather than the prognosis. Furthermore, the marginal processes in the substitution modeling were selected based on semi-quantitative methods using industry technological roadmaps. They did not consider dynamic market interaction, i.e., price elasticities, economic equilibrium, or trade barriers resulting from conflicts (e.g., sanctions). Lastly, while this study makes a compelling case for unveiling the impacts and benefits of reprocessing scenarios, subsequent stages in the LCA are missing, such as use- and end-of-life phases. Rigorous testing, such as leaching, aging, tearing, and recycling under different use and disposal conditions, is necessary for products using secondary materials. Providing these results can enable a comprehensive environmental comparison between secondary products from tailings and their primary equivalences. The ultimate goal is an extensive assessment that can strengthen decision-making and policy designs to support concrete system-wide solutions. Integrated analyses like Golev et al. (2022), combined with the presented framework, may enhance information on the sustainable management of mine tailings.

4 Conclusion

This study was set out to answer whether environmental benefits from secondary production through the reprocessing of tailings outweigh the associated environmental burdens. Built upon a previous site-specific assessment of mine tailings and future scenarios, a prospective LCA approach was employed here to assess the large-scale environmental impacts of reprocessing. Overall, the main conclusions of this analysis are as follows:

- Reprocessing copper tailings in the EU decreased freshwater ecotoxicity impacts compared to traditional waste management options. Other environmental benefits included GHG performance for scenario 2 with mineral valorization due to the large displacement of primary building materials such as cement and ceramic. However, scenario 3 with metal recovery showed an increase in climate change impacts compared to all other scenarios due to the energy-intensive metal recovery process for extracting metals at low concentrations.
- Secondary metal recovery from tailings, valorization of the mineral matrix as substitutes for building materials, and sulfuric acid production from pyrites could help meet the growing demand for these products in the EU. For building material production, the constrained availability of raw materials in the current supply of alumina sources and alkali activators could hamper efforts to scale production. This might limit the market penetration rates of these products to 10 – 15% of the total secondary supply.
- Regarding contribution to EU climate targets by 2050, around 2 – 3 Mt CO_2-eq. of savings can be generated by implementing alternative copper tailings management, equivalent to a 1.5 – 2.3% reduction in the metal industry category. Looking at the EU copper sector alone, this GHG performance is still insufficient to curb climate change compatible with the 1.5°C pathway. Additional strategies on top of what has been presented, such as demand-side

management, material efficiencies, and breakthrough metallurgical innovations, must be explored altogether to close the emission mitigation gaps meaningfully.

In summary, our findings confirm the potential opportunities for tailings reprocessing and valorization at a large scale. There are still potential pitfalls, such as the net GHG impacts of reprocessing scenarios with metal recovery, missing market demand for recovered minerals, and potential use-phase or end-of-life emissions (not studied so far). Future research shall extend the scope of the prospective LCA (use- and end-of-life) and realization of other climate mitigation strategies in the copper sector for more holistic environmental considerations. Further progress in this direction can help improve assessment quality and increase transparency in tailings-derived product evaluation.

CRediT author statement

Lugas Raka Adrianto: Conceptualization, Methodology, Software, Formal analysis, Investigation, Visualization, Writing – Original Draft. **Luca Ciacci**: Validation, Resources, Data curation. **Stephan Pfister**: Methodology, Validation, Writing – Review & Editing, Supervision. **Stefanie Hellweg**: Methodology, Writing – Review & Editing, Supervision, Funding acquisition.

Declaration of competing interest

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at DOI: www.www.com

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