Remining for Renewable Energy Metals: An Update

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Abstract

More metals are needed to accelerate the pace of using renewable energy sources to combat the climate crisis. The recovery of renewable energy metals and materials from mining wastes can become an important part of the supply chain. This updated review reports on remining efforts in four areas, with a focus on the United States and Europe: geochemical and physical characterization, estimates of the recovery potential for valuable minerals, remining examples and processing approaches, and environmental and health effects. If properly conducted, remining can improve circularity and environmental conditions in areas affected by existing and legacy mining activity.

Keywords: Remining, renewable energy, circular economy, reprocessing, characterization

Introduction

Remining can be defined as the use of mine waste, including solid waste and mine-influenced waters, as the source material from which to extract metals or create other materials with economic value. Remining sources for renewable energy metals (e.g., Co, Cu, Ni, Ga, In, Li, Mn, REEs) that are needed to expand solar and wind power and electric vehicles usage include legacy and existing mine wastes and associated mine waters, coal mine residues, and byproduct and primary production materials. Tailings are of greatest interest due to their abundance globally and the fact that they are already crushed and ground, which lowers energy and water use. Currently, remining operations are largely focused on gold; the potential for extracting renewable energy metals and minerals from mine wastes is enormous but needs more emphasis and commitment from government agencies, mining companies, and business interests.

The advantages of remining are environmental, political, and economic and include reducing dependency on foreign imports, accomplishing cleanup of the long-term environmental effects of mining while funding the cleanup through economic gain, reducing energy and water use relative to the amount of metal produced, and improving circularity – which aims to eliminate or greatly reduce wastes by creating useful products from wastes remaining from original mining and remining operations.

A paper published in 2023 (Maest 2023) examined the state of remining potential, approaches, and efforts globally in four areas: geochemical characterization, the potential for recovery of valuable minerals, remining examples and processing approaches, and environmental and health effects. This paper provides a current update on the four topics, with an emphasis on the United States and Europe.

Geochemical and physical characterization

The first step in any remining project is characterizing the volume of waste and its chemical and physical characteristics such as total metal content, mineralogy, physical stability, and worker safety issues. Phosphate, uranium, and other wastes can be radioactive, and radiologic characterization is important. Geochemical characterization methods typically applied at proposed and active mines for predicting pollution potential (e.g., acid-base accounting, short- and long-term leach tests) should be expanded to include mineral liberation analysis and bench-scale process testing for remined materials.

The U.S. Geological Survey (USGS), through its Earth Mapping Resources Initiative (Earth MRI), which began in 2019, is aiming to create a National Mine Waste Inventory (USGS 2024a). Their characterization includes bulk geochemistry for 61 elements, mineralogy by x-ray diffraction, and acid-base accounting. Water samples will be analyzed for major cations and anions, trace elements including precious metals, and alkalinity/acidity. The U.S. Environmental Protection Agency's (US EPA) Toxics Release Inventory (TRI) now has information on releases to air, land, and water from currently active mines through 2023 (US EPA 2025), but legacy mines are not included, and the data are not amenable to estimating resource potential of the mine wastes.

The European Union (EU) passed the Critical Raw Materials Act (EU 2024), which includes Article 27: Recovery of critical raw materials from extractive waste. The Article calls for establishing a database of closed extractive waste facilities in each Member State by 24 November 2026. In terms of physical and chemical characterization of the wastes, the database is to include the location, areal extent and waste volume; approximate quantities and concentrations of all raw materials; and information to enable the recovery of critical raw materials (CRMs) from the extractive waste facility.

Estimates of the potential for recovery of valuable minerals

The amount of tailings in storage worldwide was estimated at 282.5 billion tonnes in 2020, based on 8500 total tailings storage facilities (active, inactive, closed) worldwide (Franks *et al* 2020). The annual growth in tailings around the world has been estimated at between 7 and 14 billion tonnes (Maest 2023), demonstrating a wide variability due to lack of careful accounting and other factors. More recent updates on these global figures are not available.

Pollutant registries in the United States, Europe, and elsewhere can be used to get a very rough estimate of the amount of specific renewable energy metals and materials in mine wastes, but reporting improvements are needed to better estimate the metal "reserve" and to determine economic viability. The most comprehensive estimate of the amount of CRMs in tailings dates from 2019 (Blengini *et al.* 2019), and the data used in the analysis are from 2015. An update is clearly needed. Using those outdated estimates, approximately 1000 tonnes of cobalt, 2000 tonnes of gallium, 200 tonnes of indium, and 100 tonnes of natural graphite are contained in EU tailings. The preliminary economic assessment of the recovery of CRMs from extractive waste and the creation of the associated database required as part of the recently passed EU Critical Raw Materials Act will promote the recovery of CRMs from extractive waste and greatly improve estimates (European Parliament 2024).

In the United States, the US EPA updates its TRI annually. The most recently available data are from 2023. Using the TRI Explorer for all releases from the Metal Mining sector (NAICS 327), Table 1 shows the tonnes of renewable energy metals released or disposed at currently active metal mines in the United States.

Table 1 shows that total TRI releases of the selected renewable energy metals/metalloid increased from 2022 to 2023 for Sb, Cu/Cu compounds, Mn, Ni, Ag, and Zn, while all others decreased. The identity of the compounds for each chemical is not specified, and neither is the concentration of the chemical in the wastes. To better understand the potential economic value of these wastes and releases from active mines in the United States, these issues would need to be included, and other characterization methods, such as mineralogy and liberation would need to be added. Again, TRI only reports releases from active metal mines, but it does provide a picture of the amount of potentially valuable products that are thrown away and that could be added to the supply chain for renewable energy minerals.

Remining examples and processing methodology

Recent but non-exhaustive examples of remining projects in the United States and Europe are included in Tables 2 and 3. The USGS continues to expand its work under

Table 1 Total TRI releases from metal mines for select renewable energy metals: 2022, 2023, and 1998–2023

Chemical	Total TRI Disposal or Other Releases, 2022 tonnes	Total TRI Disposal or Other Releases, 2023 tonnes	Total TRI Disposal or Other Releases, 1998–2023 tonnes
Sb compounds	2289	2373	116,809
Cr	809	767	36,999
Cr compounds	4526	4372	168,593
Co	127	95.5	477
Co compounds	937	765	31,415
Cu	72	82.0	132,886
Cu compounds	38,486	39,685	2,916,356
Mn	337	392	35,560
Mn compounds	58,800	31,935	1,074,253
Ni	374	448	11,170
Ni compounds	5327	4210	141,906
Ag compounds	93	102	5968
Zn compounds	182,794	210,656	6,024,630

US EPA (2025), Maest (2023)

Earth MRI in terms of the number of sites examined for remining potential (see Tab. 2). All projects started between 2022 and 2024 are currently in progress and are still in the characterization phase. The focus on deriving value from mine wastes extends across the country from states not currently active in mining such as Iowa, to the top mining state, Nevada.

Efforts in the EU have included characterization and processing (see Tab. 3). The focus of NEMO (2025) is sulfidic wastes, and three case studies are currently underway: two in Finland and one in Ireland. Four pilot studies are demonstrating processing of the sulfidic wastes to recover metals and minerals and to emphasize circularity by creating cement and building products. Bioleaching is being demonstrated in ponds and heaps from heap leach operations and in tanks using tailings. Additional metals are being recovered from pregnant leach solution from heap leach operations. The RAWMINA Project shut down in 2024 with their final conference presentation in Barcelona in October 2024. The broad-reaching project included 19 partners in nine countries and included waste characterization, bioleaching, and selective recovery of critical minerals using four methods (see Tab. 3).

Bioleaching appears to still be the leading choice for processing of mine wastes to recover critical minerals because of its lower costs, energy use, and environmental effects, although regrinding and flotation are being used at some current remining operations (Maest 2024, Table 4 and Supplemental Materials).

In addition to governmental efforts, mining and remining companies have engaged in remining operations. Mining companies are especially well situated to evaluate the economic potential of mineral extraction wastes – whether theirs or others. A recent example is the news announcement from Cerro de Pasco Resources that their Phase 1 drilling program at the Quiulacocha Tailings Project in Peru is nearly completed (Globe Newswire 2024). Silver grades in the tailings are promising; in addition to Zn, Pb, Ag, Cu, and Au, they are focusing on Ga and In, which are important renewable energy metals. Their drilling will extend to depth in the large deposit. Mean grades to the 19-m depth drilled thus far indicate the following: Ag 1.91 oz/t, Zn 1.80%, Pb 0.77%, Cu 0.07%, Au 0.07 g/t, Ga 30.6 ppm, and In 18.4 ppm. Metallurgical testing and additional drilling (recently up to 42 m depth) are planned for 2025. The facility is estimated to contain

Table 2 Examples of mine waste and mine water remining projects in the United States. All projects are in progress.

US State	Target Mineral/ Metals	Target Waste	Mines/ Districts	Project Description/ Status
Illinois	Ba, Cd, Ga, Ge, In, Pb, Ag, U, Zn	tailings	Upper Mississippi Valley lead-zinc District	Characterization of geochemistry/ mineralogy. Started 2023
Nevada	Critical minerals	5 types of mine waste	11 sites with 4 different mineral systems	Volume, geochemical, mineralogic, deportment, resource estimate studies; Started 2024
New York	REEs	tailings	Fe, Fe-Ti, and Pb-Zn mines	Waste characterization. Started 2023
Florida	REEs, P	gypsum stacks, tailings, waste rock piles, clay settling ponds	Central and north Florida phosphate mines	Geochemical, mineralogic characterization; water samples from mine/ processing ponds. Started 2022
Montana	REEs, Ge, Zn, others	tailings	Nine mines in southwestern/ western Montana	Sampling for grade and tonnages of critical minerals, mineralogy. Started 2023
Colorado	Cd, Cu, Pb, Mg, Mn, REEs, Zn	tailings, waste rock, metallurgical waste, "perpetual mine-related water"	Ten inactive mines discharge sites, six waste pile areas (sites include three Superfund sites)	Concentrations of critical minerals in waste piles, mine effluent, and water treatment plant sludges. Started 2022.

USGS (2024b)

approximately 75 million tonnes of tailings from the 1920s to the 1990s.

Environmental and health effects

The positive environmental and health consequences of remining are mentioned much more often than the negative effects, but because the field is relatively new, few detailed examples or evaluations are available. Understanding the potential positive and negative effects of remining on the environment, ecological systems, communities, and workers is a data gap that needs to be filled as remining operations become more common.

Despite the data gap in this area, some of the same adverse effects known to occur from virgin extraction can result from remining operations, including tailings dam failures and water quality degradation. However, other adverse effects are less likely to occur from remining operations, such as creation of open pits and modification of stream flows and groundwater levels.

Because tailings are currently the primary target of remining operations, environmental and health risks associated with these mine facilities must be carefully evaluated before, during, and after remining projects. Worker safety is an especially high concern for sampling efforts. Two known tailings impoundment failures have occurred from remining operations thus far: the 2022 Jagersfontein Mine in South Africa (recovery of diamonds from old diamond mine spoil heaps) and the 2000 tailings dam failure in Baia Mare, Romania, which contaminated the drinking water of more than 2 million

Table 3 Examples of remining projects in Europe.

Countries	Target Mineral/Metal	Mine/Target Wastes	Processing Approach	Outputs / Circularity
Finland1	Cu, Co, Zn, Ni, REEs, Mn, Mg, Al, Fe, Sc	Sotkamo Ni-Co-Zn-Cu Mine / heap leach residues, pregnant leach solution	Bioleaching, secondary heap bioleaching	Critical metals and sulfates; products including backfill, cement, construction materials
Finland1	Co, Ni, Cu, Zn	Luikonlahti Mine: Cu-Zn-Ni-Co-Au ore processing facility/ high-sulfur tailings	Tank bioleaching	Critical metals and sulfates; products including backfill, cement, construction materials
Ireland1	Secondary products	Tara Mines/ tailing slimes	Flash-calcination of tailings, granulation of tailings	Cement, concrete, composite cement, artificial aggregates, ready-mix concrete
EU with partners in the UK and South America2	Co, Sb, Ge, W; additional recovery of Au, Ag	Wastes from active and abandoned mines	Mine waste characterization; bioleaching; Fe removal (magnetic); selective recovery using, e.g., nanofibrous composite materials, electrowinning, electrocoagulation	Critical metals; Fe-based byproducts

1 NEMO (2025); 2 RAWMINA (2024)

people in Hungary (WISE Uranium Project 2025). No newer tailings dam or mine facility failures related to remining operations have been reported.

Additional environmental and health risks associated with remining include leaching of metals and other contaminants to groundwater and surface water and potentially affecting aquatic life, wildlife, and drinking water sources; adverse effects on Indigenous communities, which disproportionately live close to virgin extraction projects for renewable energy minerals (Owen *et al*. 2023) and could therefore live near similar remining operations; and increased transportation, noise, and exposure effects on communities, including to radioactivity for certain kinds of deposits (phosphate, uranium).

Where remining projects also remediate existing pollution from abandoned or inactive operations, benefits can multiply. Best practices for all phases of remining operations, including for facility design, water management, worker safety, and environmental and human health protections are needed for remining projects. Many of these practices can be borrowed from those required at leading mining projects, but site-specific evaluations and approaches are always needed.

Conclusions

In addition to expanded virgin extraction for renewable energy metals and minerals around the world, recovery for mining wastes can become an important part of the value chain. Projects underway and recently completed in the United States and Europe are characterizing the "reserve" in extractive wastes, and some projects in the EU have completed or are investigating effective processing approaches. Policies are needed at the national level to encourage remining and to require environmental and worker safety protections and information transparency.

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