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Review

Remining for Renewable Energy Metals: A Review of Characterization Needs, Resource Estimates, and Potential Environmental Effects

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Abstract: Remining has been researched for decades, but its potential to supplement virgin extraction is currently unknown. This review addresses the remining of tailings/waste rock, coal residues, and byproduct and primary production materials for renewable energy metals (e.g., Co, Ni, REEs, Mn, Li). Geochemical characterization methods for estimating pollution potential must be supplemented with mineral liberation analysis and process testing to reliably estimate remining's economic potential. National and regional remining characterization efforts currently exist in the U.S., Europe, Australia, and China but will take years to produce viable operations at scale. Tailings hold the most promise due to their large amounts worldwide and the fact that they are already extracted and pre-processed, which reduces energy and water use. Of the processing approaches examined, bioleaching appears to offer the most benefits with the fewest potential downsides. The advantages and challenges of the processing methods and remining sources are presented. Best remining practices are urgently needed to improve resource estimates and avoid impacts such as the tailings dam failures that occurred at remining operations in Romania and South Africa. Interest in remining is booming because it can increase domestic supply. If properly conducted, remining can also improve circularity and environmental conditions in areas affected by existing and legacy mining activity.

Keywords: reprocessing of mine waste; renewable energy; characterization; circularity

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1. Introduction

The reprocessing of existing mine wastes as a viable source of critical minerals, especially renewable energy metals, has been discussed for nearly a decade, but the extent to which this source could complement virgin extraction at a regional, national, or global scale is currently unknown. Many efforts to evaluate the potential for remining are underway around the world, most notably in Europe, Australia, and the United States, which comprise the geographic focus of this review.

Remining can be defined as the use of mine waste, including solid and liquid waste, as the source material from which to extract metals or create other materials of economic value. The remining sources addressed in this review include wastes from abandoned hardrock mines, existing metal mines, coal mines, and byproduct and primary production. The wastes of greatest interest for remining at abandoned and existing metal mines are tailings, but smelter slag, waste rock, and mine-influenced waters are also remining targets. Tailings are already "pre-processed" because they are crushed and ground, which represents 30% of the total operating costs of mining. Therefore, although copper tailings contain only about one-third of the total copper content of virgin ore [1], economic advantages can exist for remining due to the lower operating costs.

The socioeconomic appeal of remining derives from its ability to increase domestic supply, create jobs, and improve environmental conditions in areas affected by existing and historic mining activity. Renewable energy metals from remined materials can be sourced from legacy and modern mine wastes for original target metals/minerals and for metals/minerals that were not originally targeted. Due to lower historic efficiencies, older tailings can contain, for example, from 0.2 to 0.6 wt.% Cu, while modern Cu tailings average ~0.1 wt.% [2]. The remining of wastes at abandoned hardrock mine sites has the added advantage of cleaning up long-ignored environmental impacts while deriving economic benefit from reprocessing the wastes. Changes in laws that include tax credits and other incentives can also affect the viability of remining. Wastes will still remain after remining is complete. Although the extraction of valuable metals from tailings and other mine waste has been researched for several decades [3–5], the concept of circularity in mining is a relatively new construct [6]. Circularity aims to minimize or eliminate wastes, in the context of remining, by creating products from the remaining wastes.

The renewable energy sources and metals and materials that are currently of high or moderate importance, based on their importance to energy (including energy demand, basic availability, and substitutability) and supply risk for those sources include [7–9]:

- Solar photovoltaic (Solar PV): Cu, Al
- Wind: Cu, rare earth elements (REEs), Zn
- Hydro: Cu, Cr, Zn, Al
- Concentrating solar power: Cr, Al
- Geothermal: Ni, Cr
- EVs and battery storage: Cu, Co, Ni, Mn, Li, REEs, graphite, Al.

Additional metals and materials of interest for renewable energy [10] include Cd, Ag, and Se. These three elements are currently used in thin-film technology for solar PV applications. Mn is also important for several renewable energy sources. Graphite is most important for use as lithium-ion battery anodes and for solar PV. Renewable energy technologies, especially those that can be used for battery storage, are changing rapidly, and these changes will result in modifications to critical and strategic materials lists over time. For example, passenger electric vehicles are shifting from Co toward Ni-rich cathodes in batteries [11], and alternatives to graphite for EV battery anodes are being explored [12].

The "resource" available from remining cannot be fully understood without advances in mine waste characterization and processing, which affect the economic viability of remining. Rough estimates of the total amount of certain critical minerals of interest for renewable energy are available from existing databases in the United States, Europe, and Australia, but the recoverability of the metals is still being evaluated. Active mines are more likely to have facilities available either on-site or nearby for processing. Regional processing centers for remined materials could be effective where multiple target sites exist in geographic proximity.

Environmental, worker safety, and community concerns must be evaluated to ensure that the environmental and social benefits of remining are maximized, and that remining is not creating additional or unexpected adverse impacts. Very few examples of environmental and social impact assessments or statements exist for remining, primarily because few jurisdictions require them. Best practices specifically designed for characterization, handling, processing, and remediation do not currently exist for remining sites but are urgently needed. Some best environmental and social practices can be borrowed from existing responsible mining initiatives, but certain issues are unique to remining and must be considered in the planning, operation, and closure of remining operations. Transparency and public availability of information and documents are needed to encourage responsible remining efforts and to determine public acceptance of remining.

This review addresses the current state of remining of existing mine wastes, including tailings, smelter slag, waste rock, and mine waters, and evaluates what is needed to make remining a viable source of renewable energy minerals from a technical, economic, and environmental perspective. It also presents examples of remining efforts around the world and discusses the advantages and challenges of remining.

2. Characterization Efforts

Remined materials should be treated as a resource and evaluated in a similar manner as materials for virgin extraction, including characterizing their extraction potential, evaluating the best processing methods, and predicting and mitigating environmental impacts.

2.1. Background

During the exploration of a new mineral deposit, extensive ore characterization is conducted by the mine proponent to evaluate the economic, technical, and environmental feasibility of developing the deposit. For remining, the mine wastes or byproducts are the "ore deposit", and similar characterization efforts are needed.

The total concentration of a metal in mine waste does not indicate that all that metal will be recoverable. Liberation, defined as the availability of the metal or mineral of interest for processing, is another important factor that will help to determine the most effective type of beneficiation and processing and the value or grade of the orebody. If the metal of interest is "locked" in a mineral, it will be more difficult to process. Target metals or minerals can be locked in gangue minerals, such as quartz or aluminosilicates, or in pyrite or other types of metal sulfides. Liberation can be increased by additional crushing or grinding or other methods, such as heating. Mineral liberation analysis (MLA) can be automated and provides quantitative mineralogical information, including mineral compositions, elemental occurrences, particle size, mineral locking, and liberation characteristics [13]. Although liberation is most often of interest for virgin extraction, the concept and analysis can and should be applied to remining to optimize processing approaches.

A well-known assessment of economic viability in the mining sector is the National Instrument (NI) 43-101 Standards and Disclosure for Mineral Projects. As part of this instrument, a publicly available technical report is required for any company that lists on stock exchanges overseen by the Canadian Securities Administration, no matter where in the world the project is being conducted. Because all remining projects should be treated the same as virgin mineral extraction projects in terms of assessing their economic and environmental viability and consequences, requiring NI 43-101 reports, or publicly available reports with similar requirements, for all remining projects would increase transparency for investors and the public.

2.2. Sampling and Characterization Efforts for Remined Materials

Potential remining projects must begin with an estimate of the total amount and type of waste and collection of samples from the "deposit" to determine the concentrations or percentages of metals of interest. A detailed sampling plan is needed that includes procedures for sample collection, handling, preservation, and analysis—and for ensuring the safety of the sampling team. Blannin et al. [14] describe the sampling protocols used for assessing critical raw material specifically in tailings facilities. Characterization in the remining context refers primarily to chemical characterization but must also include characterization of the materials for physical characteristics, physical stability, and worker safety. Lottermoser [15] notes that new macro-, meso-, and micro-scale characterization methods are needed to increase confidence in mine waste characterization and to promote circularity.

Guidance is needed on sampling and reporting procedures to ensure that consistent information on the "ore grade" of a waste resource is known. The chemical and physical characteristics of remining materials will also affect the environmental behavior of the operation during and after it is completed.

2.2.1. Sampling

Mine wastes are not yet treated as a resource, and sampling and characterization schemes or best practices for gathering representative samples for remining are not available. Much of the effort expended thus far on remining has focused on tailings. Depending on the type of depositional environment used, tailings are generally more consistent in particle size, chemical composition, and physical characteristics than waste rock. However, tailings deposited as slurries into tailings storage facilities can be highly heterogeneous in terms of the minerals of interest, locations within the impoundment of high and low metal content, and particle size [14]. Pan et al. [16] show the large variability in element concentrations with depth in two tailings impoundments in China (concentrations are generally higher at depth), demonstrating the importance of sampling more than the easily reached upper parts of repositories. Knowledge of particle size is important because smaller particle sizes (e.g., slimes) can be more difficult to float but can also contain higher concentrations of metals [17].

Because most tailings were deposited wet rather than filtered, safety concerns for sampling also exist—especially if the impoundment has not been adequately drained over time or sampling occurs close to the time of deposition. The methods used by the U.S. Environmental Protection Agency (U.S. EPA) for waste sampling can provide a good starting point for remining projects (see, e.g., [18]). Geostatistical sampling methods should be applied to determine the value of tailings, waste rock, and other mine waste materials targeted for remining, as they are for determining the value of virgin ore bodies. The Pan-European Standard for Reporting of Exploration Results [19] contains guidance for the sampling and reporting of mineral resources and reserves. Blannin et al. [14] argue that statistical investigations on appropriate sampling strategies and resource classification methods for resource recovery from tailings are still completely lacking, but they designed a geostatistical modeling and sampling protocol for estimating the critical raw material value of a tailings storage facility. Examples of geostatistical modeling methods include ordinary kriging, sequential Gaussian simulation, conditional simulation, turning bands co-simulation, and ordinary co-kriging [14]. Mulenshi et al. [20] argue that sampling schemes must be site-specific and dependent upon the environmental and resource recovery concerns and aims for the tailings deposit. Given the general lack of information on changes in metal concentrations with depth in tailings impoundments, reliable geostatistical sampling approaches could be even more challenging. Sampling approaches for valorizing waste rock could be even more challenging because of the inherent heterogeneity in waste rock versus tailings.

2.2.2. Geochemical Characterization

The geochemical mine waste characterization methods used for environmental or mine management—such as total metal concentrations, short- and long-term leach tests, and acid-base accounting tests [21]—are necessary but insufficient for evaluating the waste as a resource. For example, while many mines collect continuous tailings data on bulk chemistry (i.e., total metal content), density, and particle size distribution, details on mineralogy, particle microstructure, and weathering effects are rarely monitored [22]. Certain mine wastes may be radioactive, such as those from phosphate wastes that contain monazite, an REE phosphate mineral [23], and estimates of radioactivity will be needed. A generalized flow diagram for characterizing and managing tailings for remining is shown in Figure 1. Such an approach would allow for estimates of the economic value of the waste and predictions of its environmental effects.

Zhang et al. [13] present a case study that applies MLA and other metallurgical testing methods to Cu sulfide tailings in Zambia. Their results showed that nearly all Cu sulfide minerals in the tailings were disseminated in coarse gangue particles, although the tailings did contain more than 3 wt% liberated, fine-grained chalcopyrite and bornite. Improving the recoverability of Cu in flotation operations will decrease the amount of Cu in tailings, but the same approaches and understanding can be applied to improving copper recovery in remined sulfide tailings.

Many of the current remining operations, including companies that specialize in remining, are targeting Au in tailings. Metallurgical testing, including MLA, was conducted on of a series of historic (1934 to 1980) sulfidic gold tailings impoundments and piles in the Nova Lima region in Brazil [24]. The results demonstrated that 70% of the Au in sulfide tailings was recoverable, identified other metals contained in and uses for the tailings after remining, and can be applied to other mine waste deposits.

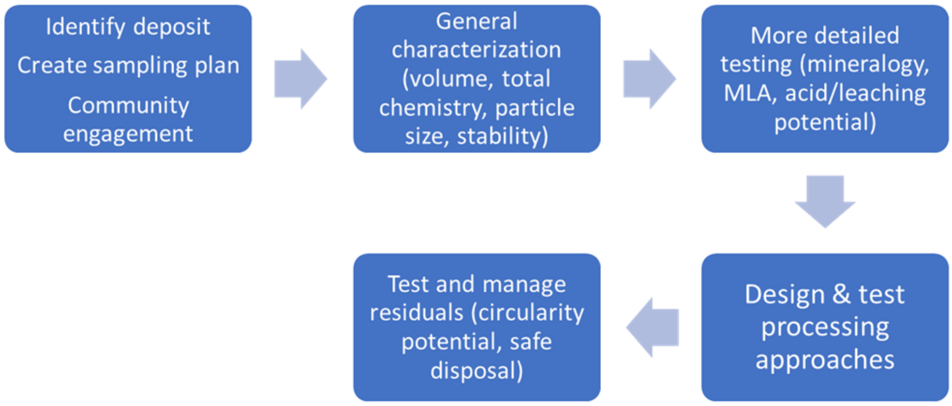

Figure 1. General approach for characterizing and managing tailings for remining.

Remining does not result in the reprocessing of all the tailings and leaves much of the original waste as a more final waste product. As noted by Mulenshi et al. [20], residue management also includes residue characterization and assessment for recycling or reuse (e.g., as construction materials, if chemically and physically appropriate), and/or disposal. Because the historic or existing waste is rehandled, the potential exists for more secure disposal after remining using liners, caps, and other protections. The potential also exists for physical stability problems.

2.2.3. Physical Stability Characterization

Evaluating physical stability is essential for remining projects that source their materials from wet, dammed tailings impoundments or that create new or expanded wet, dammed tailings impoundments after remining is completed. While filtered tailings facilities (also known as "dry stack" tailings) have a lower water content than those using wet slurrying, they can nonetheless fail. A failure at the Pau Branco iron mine in Nova Lima, Minas Gerais, Brazil, occurred on 8 January 2022, and was caused by the heavy rains that caused mud from the filtered tailings facility to flow into a water storage pond and breach the dike of the water retention pond [25]. Pipelines bringing tailings from one location to another, such as in the Baia Mare tailings remining project, can also burst or leak and should be constructed using the best available technologies (e.g., double-lined pipes). Several guides or standards [26–28] include safety and monitoring criteria and recommendations for evaluating the physical stability of tailings impoundments.

2.3. Planned or Ongoing Chemical and Economic Characterization Efforts at the National, Regional, and International Levels

Larger-scale characterization and evaluation of remined resources are being carried out in the United States, Europe, and Australia, and are discussed in this section. Pollutant registries for mine wastes can also be applied as initial information for remining. In general, these efforts will take years to produce results that can be applied on a larger scale.

2.3.1. United States

The U.S. Geological Survey (USGS) is developing and refining hyperspectral imaging and other methods to determine the potential for mine wastes to contain critical minerals [29]. The USGS's Earth Mapping Resources Initiative (Earth MRI) is in the early stages of conducting a ten-year assessment of mine waste sites in the United States, with a current focus on critical minerals in tailings and "perpetual waters," and has designated pilot sites in a growing number of states, including Colorado, New Mexico, Florida, Illinois, New York, and Washington [30]. The priorities of the program are to create a current and historical national mine waste geospatial database and to conduct a mine waste characterization assessment to inform critical mineral endowments and reclamation decisions. The program will determine the number and location of mine waste sites, how much material is available that may contain critical minerals, the tonnage and grade of the material, and the geological, geochemical, and mineralogical characteristics that may influence the recovery of the commodities of interest and environmental impacts. The U.S. critical mineral list is updated every three years [31], so a wide net is being cast in terms of metals and mineral characterization. Solid phase samples (primarily tailings currently) will be analyzed for bulk geochemistry, including 61 elements, mineralogy by X-ray diffraction (XRD), and acid-base accounting. Water samples (primarily perpetual waters currently) will be analyzed for major cations and anions, trace elements including precious metals, and alkalinity/acidity. The USGS is also working with the U.S. Department of Energy on legacy mine site characterization methods and technologies [32].

The U.S. Environmental Protection Agency (U.S. EPA)'s Toxics Release Inventory (TRI) contains information on the metal content of mine waste discharged to land, water, and air for all currently operating metal mines. A facility is required to report if it: (1) falls within a TRI-covered industry sector (metal mines are included) or is federally owned or operated; (2) has 10 or more full-time employee equivalents; and (3) processes more than 25,000 pounds or uses more than 10,000 pounds of a TRI-listed chemical in a calendar year [33]. In 2021, the most recent year with available TRI data at the time of writing, a total of 87 mine facilities reported to TRI, and the metal mining sector accounted for 68% of land disposal quantities. No strict sampling or reporting requirements exist for TRI estimates, but a 25-year-old guidance document has recommendations for the metal sector [34]. The metals reported to TRI that are of current interest for renewable energy are:

- Sb compounds
- Cr/Cr compounds
- Co/Co compounds
- Cu/Cu compounds
- Pb/Pb compounds
- Mn/Mn compounds
- Mo trioxide
- Ni/Ni compounds
- Ag compounds
- V compounds
- Zn compounds.

For the metals and metalloids that include "compounds," the amount of the metal in the compound is not known or reported. The amount of a metal compound can be estimated using different approaches and compared to reporting thresholds for metal compounds. If the type of compound is known (e.g., a Cu sulfide mineral), the facility may assume that the compound exists as the lowest weight Cu sulfide [34]. For example, for Cu compounds, covellite (CuS), contains 66.5 wt% Cu. Similarly, assuming Mn is present as an oxide, MnO_2 contains 63 wt% Mn. In this study, the amount of metal in metal compounds is assumed to be 50% of the reported mass to facilitate adding the TRI-reported amounts of metal and metal compound. Improved reporting of the identities of metal compounds would help estimate the total amount of metal in a waste.

Al and Zn, as metals, are only required to be reported if they are released to air as fume or dust. However, the amount of Zn compounds in waste is required to be reported. Fe is not required to be reported at all to the TRI. Al, Fe, and Zn are important metals for wind, solar PV, hydro, and energy storage [7]. Because Al, Fe, and, to a much lesser extent, Zn, are so ubiquitous in mined ores and wastes, reporting the amount of these metals in waste could be misleading in terms of potential adverse environmental impacts. But the lack of reporting of Al, Fe, and Zn as metals in wastes released to land and water makes it impossible to know if these releases could be used as a remining source for renewable energy.

The reporting results from TRI make it possible to estimate the amount of metal in land-disposed mine waste in a given year. However, the guidance for the reporting of metals to the TRI makes it nearly impossible to determine the "ore grade" of a metal of interest in mine wastes at a given mine. Improvements in reporting requirements for TRI would make this tool much more useful for estimating the value of mine wastes at active mines.

2.3.2. Europe

The European Commission [35] released drafts of its Critical Raw Materials Act Proposal on 16 March and 30 June 2023. The Proposal includes Article 26, Recovery of critical raw materials from extractive waste, which obligates operators to submit waste management plans and a preliminary economic assessment study on the potential for recovery of critical raw materials from extractive wastes within three years from the regulation being enforced. The study must include an estimate of the quantities and concentrations in the waste and an assessment of their technical and economic recoverability. Each Member State is required to establish a publicly accessible and digital database of all closed waste facilities (including abandoned sites) in their territory, listing the location, areal extent and waste volume of the waste facility; the names of the operator, successor, or former operator; the approximate quantities and concentrations of all raw materials in the waste and, where available, in the original mineral deposit; and any relevant information to enable the recovery of critical raw materials. If a waste facility potentially includes (does not exclude) economically recoverable critical raw materials, a representative geochemical sampling must be conducted. For waste facilities that indicated potentially economically recoverable quantities of critical raw materials, Member States must conduct a more detailed analysis using core logging or similar techniques in accordance with applicable environmental requirements. Member States must, where possible, also include a classification of the closed extractive waste facilities according to the United Nations Framework Classification for Resources.

The databases used in the European Union (EU) for raw materials included ProSUM (Prospecting Secondary raw materials in the Urban mine and Mining waste project (2015–2017)), which included data on mining waste stored as an extension to the Minerals4EU database, and ORAMA (Optimising quality of information in Raw Materials data collection across Europe (2018–2019)), which includes data from the Czech Republic, Denmark, Croatia, Ireland, Norway, Sweden, Slovenia, and Ukraine. The European Pollutant Release and Transfer Register (E-PRTR) provides public access to environmental data from industrial facilities, including mining and quarrying, in EU Member States, Iceland, Liechtenstein, Norway, Switzerland, Serbia and the UK. Like the U.S. TRI, the E-PRTR only includes total releases in kilograms. Only minimal information is available on land releases using the E-PRTR. For example, for the mineral industry sector, only Cu, Cd, Cr, Pb, Ni, and Zn are available, and only for underground mining operations for limited years (see https://industry.eea.europa.eu/analyse/summary-table; (accessed on 18 September 2023). In contrast, reported releases to water are generally higher than land releases, are available for underground and opencast mining and quarrying operations, and are available for more analytes and more years (2007–2021). According to Kinnunen et al. [36], the current national mining waste registries in Europe are too generic to provide information on the recoverability of critical raw materials from mine waste (for example, no information on concentrations or impurities is included). Žibret et al. [37] examined the national mine waste registries for seven European countries and also concluded that they could only serve as an initial source of information on remining because the focus is primarily on the wastes as a potential source of pollution.

In addition to pollution registries, and as noted by Rosario-Beltre et al. [38], the EU is engaged in several broad-reaching remining projects, including RAWMINA (https://rawmina.eu/; accessed on 2 November 2023), with partners in the UK and South America, and NEMO (https://h2020-nemo.eu/project-2/; accessed on 2 November 2023), which aims to valorize low-grade sulfidic mine waste to recover critical raw materials.

2.3.3. Australia

The Australian Government publishes a National Pollutant Inventory (NPI) that tracks pollutants released from industries across Australia, including the mining sector [39]. The NPI provides public access to information about the emission and transfer of 93 toxic substances to air and water. Reporting started in 1998, but the list of substances and reporting limits has changed over time. The current substances list includes the following metals and elements (metal and metal and compounds are reported together): Sb, As, Be, Cd, Cr (III and IV reported separately), Co, Cu, Pb, Mn, Hg, Ni, Se, Zn.

The Australian Government [40] recently created the Atlas of Australian Mine Waste, an interactive online mapping tool with information about Australian mine tailings, waste rock, smelter residues, and related mine waste materials. The Atlas is specifically designed to help identify opportunities for the supply of critical minerals from secondary sources. Downloads of the data include the mine name, location, waste type, deposit type, waste structure, and waste status, but currently contain no information on the chemical content of the wastes. However, a project for the State of Queensland is underway. Dr. Anita Parbhakar-Fox of the Sustainable Minerals Institute is leading a University of Queensland team working on a four-year, AUD 1 million project with the Queensland Government's Department of Natural Resources, Mines, and Energy to examine new economic metal concentrations in Queensland's mine wastes. Given the large amount of mine production in Australia [41], Australia's mine wastes could make a substantial contribution to sourcing metal resources.

2.3.4. OECD

The OECD publishes a broader inventory of pollutant releases from Australia, Canada, Chile, the EU (E-PRTR), Japan, Mexico, and the United States [42]. As with the other registers, releases are presented in total kilograms of selected pollutants and are limited to air and water releases (releases to land are not included). The pollutants relevant to the metal mining sector are Cd, Cr, Hg, and Ni (metal and metal compounds are reported together). Several industrial sectors, including mining and quarrying, are included. Data are currently available from 2008 through 2017.

3. Potential for Recovery of Valuable Minerals

The potential for recovery of critical minerals and metals from sources such as tailings, waste rock, coal ash, acid mine drainage (AMD), and ore-processing facilities (e.g., electrowinning anodes) is currently difficult to estimate because characterization and processing of the sources are generally in the early stages of development. Examples of recovery potential have been provided for specific sites, but they rarely take the costs of characterization, processing, transportation, and construction of needed facilities into account. In general, the reprocessing of tailings or waste rock is more likely to be able to use existing infrastructure, especially at operating mine sites. Importantly, the potential for recovery of critical minerals for renewable energy must also consider community acceptance, worker safety, and environmental effects.

For virgin extraction, different levels of resource estimates are made based on multiple factors and are divided in the broader and less reliably estimated mineral resources compared to the economically mineable part of the resources, mineral or ore reserves; both are usually reported in terms of grade and tonnage [43]. For remined sources, as for virgin mining sources, it is not possible to economically or technically extract and process all the metal in the wastes.

Despite these limitations, estimates of the mass of mine waste and the total amount of renewable energy metals in the wastes can provide a rough idea of the potential for mine wastes to serve as important sources of metals for the new energy economy. The findings show that the estimates are very rough, and, in some cases, outdated, and further characterization of mine wastes is needed.

3.1. World-Wide Estimates

The amount of mine waste produced per unit of mined commodity has increased over time due to declining ore grades. An estimated 8500 active, inactive, and closed tailings storage facilities exist worldwide [44]. Using their estimate for the volume of tailings in facilities listed in public disclosures and extrapolating to 8500 total facilities, roughly 217 billion m3 of tailings are in storage globally. Franks et al. [44] estimate the annual growth in tailings from 2020 to 2025 at 11.1 billion m3. A separate and similar 2015 estimate suggests that the mining industry produces ~14 billion tonnes of tailings annually [45], Marín et al. [46] estimate global annual tailings production at between 5 and 7 billion tonnes, and Mudd and Boger [47] estimated global tailings and waste rock production in 2011 at more than 7 billion and 55 billion tonnes, respectively. All these values are estimates based on global mineral production from the USGS and other sources and show uncertainty in the overall amount of tailings in storage and produced annually worldwide. While there is clearly no shortage of tailings as a potential source material for recovery of renewable energy metals, the "resource" and "reserve" of the deposits have not been estimated.

Some mined commodities produce a higher percentage of the world's tailings than others: Cu accounts for 46%, Au for 21%, followed by Fe (9%), coal (8%), phosphate (4%), Pb/Zn (3%), Ni (2%), and other commodities (7%) [48]. Zhang et al. [13] estimate that sulfide tailings generated from Cu mines account for more than ~27 million tonnes of tailings worldwide, of which almost 90–95% are produced from the flotation process.

Patel et al. [49] estimate total REE concentrations, and the concentrations of some individual REEs, in fly ash, coal ash, red mud, mine tailings, and other industrial wastes in 11 countries around the world. The highest REE concentrations are found in REE magnet scraps (up to 36.7%, or 36,700 mg/kg, for multiple REEs), but concentrations are also high in red muds (up to 1777 mg/kg in Greece and Turkey). While the concentrations suggest potential for secondary recovery, the total REE amounts were not provided.

3.2. Regional Estimates for the EU

A survey of mines across Europe conducted by the BRGM [50] gathered data on the waste quantities produced for the whole period of mining activity (from the middle of the 19th century, although for some sites' data went back to Roman times) in four categories: ferrous metals, non-ferrous metals, industrial metals, and coal—including known closed and abandoned mine sites. The total amount of waste rock and tailings, and the amounts stored for each of the four categories, were reported. The countries queried included Denmark, Finland, France, Germany, Greece, Ireland, Portugal, Spain, Sweden, and the United Kingdom. Coal waste volumes were the largest. The results, although inconsistent across countries, showed that more than 4.7 billion tonnes of mining waste and more than 1.2 billion tonnes of tailings waste were stored at that time in the EU [50].

According to Blengini et al. [51], no EU or Member State database reports the volumes of extractive waste for closed or active mines disaggregated by targeted mineral or waste type—or the volumes of the different extractive waste streams. However, the material system analysis (MSA) study investigated the flows and stocks of 28 raw materials from "cradle-to-grave" and produced a comprehensive inventory of extractive waste disposed as tailings annually, and the "stock in tailings," which is the accumulated amount of tailings in the EU over time. The estimates for certain metals of importance to renewable energy include totals of approximately 1000 tonnes of Co, 2000 tonnes of Ga, 200 tonnes of In, and 100 tonnes of natural graphite in EU tailings. These are the most recently available estimates on remining source materials in the EU, and they date back to 2012. An update on tailings and mine waste mass and volume and chemical compositions should be conducted as soon as possible. The same edited volume [51] estimated the amount of bauxite residue (red mud) from alumina industry across Europe as 7 million tonnes per year (dry basis) and noted its importance for REE/Sc recovery. The extraction of REEs from Mytilineos's (Greece) annual red mud production was estimated to meet ~10% of European demand for REEs [52]. The same paper estimated that extracting Ga from the red mud and the Bayer liquor from just one European alumina refinery would be equivalent to global levels of gallium production (annual world production in 2012 was 284 tonnes).

The potential for recovery of Mo, Nb, Re, Ta, and W from secondary resources, especially mine wastes, across Europe was evaluated in 2016 as part of the MSP-REFRAM project, funded by the EU [53]. The project reported concentrations and tonnages, when available, using the dataset from PROMINE and other sources. The number of sites in Europe with recovery potential calculated using data from PROMINE was the highest for Mo and W (28 and 24 sites, respectively) and lowest for Nb, Re, and Ta (with 8, 1, and 0 sites, respectively).

The information required in the Critical Raw Materials Act Article on remining, assuming it remains in the final version, will provide much-needed updated information on remining potential across Europe.

3.3. Estimates for the United States

The United States requires active metal mines and many other industries to report their emissions to land, air, and water annually as part of the US EPA's Toxics Release Inventory (TRI; [33]), and many of the metals that are required to be reported are considered critical metals for renewable energy. Publicly available data from the TRI were used to calculate the amount of cobalt compounds for the top 10 releasers in 2021 (Table 1). The amount of metal compounds reported is much higher than the amount of metal reported. The total amount of cobalt compounds released in 2021 totaled 703 tonnes. None of the mines are primary Co mines; and Co is primarily produced as a byproduct of Cu production. However, the Co content in wastes from the mines listed in Table 1 are from tailings or other mine wastes, not from byproduct production.

Table 1. Top 10 U.S. mines with releases of cobalt compounds, TRI data, 2021.

Facility, State	Primary Commodity	Total TRI Releases (tonnes)
Eagle Mine, Michigan	Cu, Ni, Pb, Zn	172
Montana Resources, Montana	Cu, Ni, Pb, Zn	147
Freeport-McMoran Miami, Arizona	Smelt./refining	101
Freeport-McMoran Morenci, Arizona	Cu, Ni, Pb, Zn	50
Carlin South, Nevada	Au	47
Phoenix, Nevada	Au	45
Goldstrike, Nevada	Au	43
Oceanagold Haile, S. Carolina	Au	34
Turquoise Ridge, Nevada	Au	33
Cortez District, Nevada	Au	32
Total, 2021 (Top 10 only)		703

Source: [33].

Similarly, the TRI data from 2021 were used to calculate the total amount of Ni compounds for the top 10 releasers in 2021, which totaled 5210 tonnes (Table 2). Three of the mines list Ni in their primary commodity type, and many of the same mines with the highest reported releases of Co compounds also have the highest reported amounts of Ni compounds, as expected because these base metals can occur together in certain ores.

The total TRI releases to land, water, and air from all metal mines for metals of interest for renewable energy are listed in Table 3. As noted previously, metal and metal compounds cannot be added together because the composition of the metal compounds is not listed in the TRI data. Assuming that the amount of Cu in "Cu compounds" is 50% of the amount listed in Table 3, and, adding to that the amount reported for "Cu," the total amount of Cu released to the environment from metal mines as waste in 2021 was 24,395 tonnes.

Table 2. Top 10 U.S. mines with releases of nickel compounds, TRI data, 2021.

Facility, State	Primary Commodity	Total TRI Releases (tonnes)
Eagle Mine—Humboldt Mill, Michigan	Cu, Ni, Pb, Zn	2949
Red Dog Mine, Alaska	All other metal ore	1034
Goldstrike Mines, Nevada	Au	429
Stillwater—Nye Mine, Montana	All other metal ore	201
Carlin South, Nevada	Au	183
Stillwater—East Boulder Mine, Montana	All other metal ore	118
Montana Resources, Montana	Cu, Ni, Pb, Zn	115
Eagle Mine, Michigan	Cu, Ni, Pb, Zn	64
Oceanagold Haile, S. Carolina	Au	59
Turquoise Ridge, Nevada	Au	58
Total, 2021 (top 10 only)		5210

Source: [33].

Table 3. Total TRI releases from metal mines for metals of interest for renewable energy for 2021 and 1998–2021 compared to U.S. annual consumption.

Chemical	Total TRI, 2021 (tonnes)	U.S. Annual Apparent Consumption (tonnes) [a]	Total TRI, 1998–2021 (tonnes)
Sb	0	27,000	786 [b]
Sb compounds	2163		112,147
Cr	1025	590,000	35,423
Cr compounds	3746		159,695
Co	100	7800	255 [c]
Co compounds	665		29,713
Cu	78	1,900,000	132,732
Cu compounds	48,635		2,838,186
Mn	304	890,000	34,831
Mn compounds	52,033		983,519
Ni	310	220,000	10,348
Ni compounds	5355		132,370
Ag	0	6400	159 [d]
Ag compounds	79		5773
Zn compounds [e]	180,321	910,000	5,631,180

[a] For metal/metalloid using the most recent data (2022); [b] Only reported in 1998 and 1999; [c] Not reported in meaningful amounts (either not reported or ≤160 lbs total annually) until 2017; [d] Only reported in 1998, 1999, 2000, 2014; [e] TRI Zn is reported as fume/dust (to air) or compounds, annual consumption is for refined Zn. Sources: [33] (using TRI Explorer and selecting for each Year of Data from 1998–2021) [54].

Table 3 includes all TRI releases from 2021 and from 1998 (first year of reporting for metal mines) through 2021. Note that the totals for RCRA Subtitle C surface impoundments, other surface impoundments, and other land disposal combined (in other words, land disposal) are nearly 100% of all on-site releases for the metals of interest. Off-site releases are minimal compared to on-site releases. Therefore, metal releases from metal mines are almost exclusively to land impoundments such as waste rock or tailings facilities. Inconsistencies in the years of reporting, especially for certain metals, and large differences between totals reported in earlier and later years, are an indication of the uncertainties in the TRI numbers. The mass of metals reported dropped considerably after Barrick Gold won a ruling against EPA/Whitman in 2003 regarding the reporting of amounts in waste rock. After April 2003, if concentrations were <1% in waste rock, reporting was not required. The totals in Table 3 include all years between 1998 and 2021.

Using the values in Table 3 for Mn, Ni, and Co, and assuming that 50% of the reported metal compound is the metal of interest, the totals for these metals would be 26,320 tonnes of Mn, 2987 tonnes of Ni, and 432 tonnes of Co in a single year (Figure 2). Using USGS values for metal consumption in the United States in 2022 (the most recent available year [54]), between 1.4% (for Ni) and 5.5% (for Co) of the U.S. annual consumption is thrown out in mine waste each year. Note that the annual consumption is for all uses of the metal; use for renewable energy is not tallied separately, although the Ni price increased by 35% from 2021 to 2022 due to increases in the use of Ni in electric vehicle batteries and the continued strong demand for stainless steel [54]. Table 3 also provides the total TRI releases from 1998–2021 and indicates the much higher potential stock of metals released from active U.S. metal mines since metal mines have been required to report to the TRI (Figure 2). Given the total stock of mine waste in the U.S., including at historic and active mines, mine waste could be a substantial resource for renewable energy metals. Of course, the estimated total amounts would not be completely recoverable, and more work is needed to estimate the metal reserve in mine wastes.

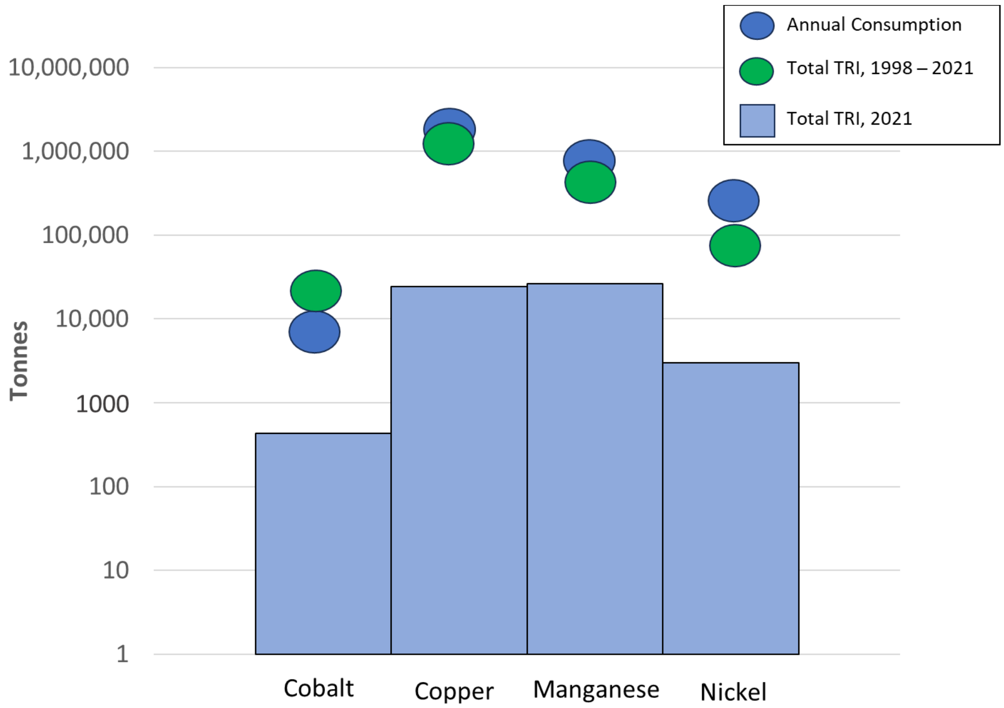

Figure 2. Potential for metals disposed or released from active metal mines in the U.S. to supply annual consumption. Sources: [33,54].

3.4. Estimates for Other Countries

Finland: In Finland, Kinnunen et al. [36] showed basic characterization data for 19 mines in Finland regarding the size of the deposit, the grams/tonne content, and the presence of infrastructure. The results show that mine tailings across Finland contain Ni, Co, and Zn worth 100 s of millions of Euros, but this value is based solely on total concentration and does not consider processing costs and other factors, such as accessibility.

Chile: Cacciuttolo and Atencio [1] assessed tailings masses, management strategies, and relevant regulations in Chile, which is by far the largest Cu producing country in the world. Chile produces 800 million tonnes of mining tailings per year, or approximately 2,192,000 tonnes per day. Between 1905 and 2022, Chile's Cu mining operations have generated 13 billion tonnes of tailings, covering a surface area of 26,876 hectares [1]. Tailings in Chile also contain Co, V, Ga, Ge, and REEs. Given the enormous amount of Cu tailings in Chile, the initial discovery of metals needed for renewable energy sources in the tailings, and recent advances in the use of best management practices, including filtered tailings, the potential for remining tailings for renewable energy metals is promising and should be further evaluated.

Spain: The Iberian Pyrite Belt (IPB) in Spain and Portugal is considered the most important mining district in Spain and Europe [38], and several efforts have been directed toward metal recovery from mine wastes and acid mine drainage waters. Bulk metal concentrations and mineralogy were evaluated in legacy (19th–20th century) roasted pyrite wastes in the IPB by Yesares et al., 2023 [55] and found to contain potentially economic concentrations of Pb, Cu, Zn, Ag, and Au. Rosario-Beltré et al. [38] summarized information from mine wastes across all of Spain and conducted grain size, mineralogic, and chemical analyses of the most promising 20 mine waste facilities in terms of the recovery of elements with economic potential, many of which are included in the EU's list of critical raw materials. Two of the facilities with the most promising economic potential are found in the IPB, and the highest economic potential is estimated to derive from Tl, Ag, and Sc. Their combined economic potential, based solely on total concentrations and estimated tonnage, is estimated at USD 2.6 million. Acidic drainage, primarily from waste rock piles in the IPB, also holds economic potential for the recovery of Co, Cu, Zn, Mn, and other elements. Cánovas et al. [56] focus on the environmental effects of releases from sulfide wastes in the IPB and mention that metal recovery could improve environmental conditions; however, they note that more work is needed to determine grade, mineralogy, and recovery methods. Fortes et al. [57] evaluated 33 mine drainages in the IPB and estimated that, considering the total area of abandoned mine waste dumps in the IPB and measured concentrations in the acidic discharge, more than 400 million USD/yr could be realized from metal recovery of these polluted waters. Bonnail et al. [58] also investigated the recovery of clean water and metal compounds from AMD in the IPB using a passive dispersed alkaline substrate technology and adiabatic sonic evaporation and crystallization, which could be fueled by renewable energy and requires no pretreatment. The methods could be applied to improve ecosystem services in the Tinto and Tinto-Odiel rivers, which currently transport large amounts of metals annually, including 1.3 tonnes Y, 248 kg Sc, 139 kg Ga, 3500 tonnes Zn, 1700 tonnes Cu and 1600 tonnes Mn.

China: China initiated the Nationwide Geochemical Survey and Evaluation of Mine Tailings Project in 2010, and, as of 2014, 291 drill holes and 9747 core samples were collected from 26 tailings impoundments in 23 metal mining areas in the country [16]. The 3D distribution of elements was determined, a 3D tailings model was created, and beneficiation tests were conducted on one of the tailings impoundments (Hongqilin nickel mine in Jilin). Higher concentrations of a variety of metals and elements were found at depth in the tailings, due to the use of less efficient beneficiation methods in the past [16]. Based on the average measured metal concentrations and tailings amounts, up to an estimated 57,860 tonnes of Cu, 62,000 tonnes of Ni, and 112,000 tonnes of Zn are available in single tailings impoundments in China [16]. In addition, a tailings impoundment at an iron mine in Mongolia reportedly contains up to USD 12.8 trillion in REEs [59]. More updated information is needed to assess current estimates of remining metal recovery potential for China.

Although the total amount of renewable energy metals in mine wastes, especially in tailings, has been estimated in many countries and regions around the world, a more detailed characterization of the recovery potential from remined sources is generally lacking. Such an assessment will need to comprehensively evaluate: viable sampling and characterization methods; metallurgical properties that can affect processing choices; the total amount of recoverable metal in the resource and reserve considering economic and other factors; the accessibility of the remined resource; whether reprocessing can occur on-site, nearby, or at a distance that will require waste hauling; and the potential positive and adverse effects on the environment, human health, and the local and regional economy. The findings of these assessments can be used to prioritize sites for remining. The very large amount of mine waste worldwide points to the promising potential for recovery of renewable energy metals from these sources, and further characterization of the economic potential and environmental advantages and challenges is needed to better understand that potential.

4. Remining Examples and Technical Feasibility

Proving the economic and technical feasibility of a remining project requires not only promising source materials and good characterization results, but also the infrastructure and scientific and engineering experience of those conducting the remining activities. Examples of remining projects are included in the Supplementary Materials.

4.1. Examples of Mine Waste Characterization or Remining Projects and Corporate Ventures

Many remining case studies exist, but the majority are in various stages of characterization or laboratory and bench-scale investigation to determine the most effective processing methods. Some other examples are only in the planning stage, and references may include company or organizational announcements (e.g., press releases) rather than published articles. Often, the advantages of remining and reprocessing are discussed, but the potential downsides or challenges are not mentioned.

The examples provided in the Supplementary Materials are not meant to be exhaustive but rather to offer a sense of the geographic and chemical breadth of the interest in remining. Excluding the remining companies, which have focused primarily on gold, all examples in the Supplementary Materials are of projects that target renewable energy metals or that do not exclusively focus on precious metals.

Examples include remining projects targeting metals from tailings, coal ash and waste, secondary recovery from ore production byproducts, AMD and sludges, and projects from remining companies. Nearly all the projects are in the characterization or economic evaluation phase, although several have established laboratory phases to examine the most effective processing methods. One project, owned by Rio Tinto, has completed a pilot-scale project to produce Li from waste rock at Rio Tinto's boron mine in California, U.S.

The projects in full operation are:

- Kasese Cobalt site in Uganda: recovery of Co from former Cu mine tailings using bioleaching methods
- Golden Sunlight Mine, Montana, U.S.: recovery of Au from existing Au tailings using existing facilities
- DRDGold, South Africa: recovery of Au from former Au mine dumps and tailings
- New Century Project, Australia: recovery of Zn from former Zn/base metal tailings
- Pan African Resources, South Africa: recovery of Au from historic Au tailings.

The projects in full operation demonstrate the preference for tailings as remining targets, and, in general, the targeting of Au for recovery from the tailings. Nearly all the projects are owned and operated by mining companies. In addition to the research projects undertaken at universities and government agencies, for-profit companies interested in remining are proliferating. Most companies in the remining business are targeting Au and other precious metals, but the global imperative for expanding renewable energy technologies is increasing interest in associated metals with the potential for increasing profitability.

4.2. Technologies and Processing Approaches

After the remined materials have been physically and chemically characterized, extraction and processing methods must be assessed, which will then feed into economic and environmental evaluations of the remining project.

4.2.1. Mine Waste Reprocessing Methods

Review articles by Sarker et al. [60], Kinnunen et al. [36], and Whitworth et al. [61] discuss processing approaches for mine waste, especially tailings. The most commonly applied remining processing methods are described in Table 4. Although phytomining and solvometallurgy could be used to extract metals, both are considered novel; neither method has yet been tested at a large scale by the mining industry, and solvometallurgy has relatively high reagent costs and viscous solutions that complicate physical separation steps [61]. Processing methods are often used in combination to recover metals of interest from mine wastes. Most tailings retreatment processes use proven technologies that have been applied to richer and less complex ores and are therefore considered technically feasible for tailings treatment. The economic feasibility is more complex, in part due to the generally lower concentrations of metals of interest [36].

Table 4. Most common remining processing methods and their challenges and advantages.

Processing Method	Description	Challenges	Advantages	Notes/Relevant Metals
Hydrometallurgy	Broad category that includes flotation, bioleaching, and leaching with chemical reagents (e.g., heap, dump, vat leaching); often followed by separation of metal ions from solution using precipitation, solvent extraction, and membrane methods.	Leaching with strong acids or bases generates a large amount of waste that can make recovery ineffective and lead to environmental and worker safety concerns from high concentrations of toxic chemicals.	Versatile and proven technology for mined ores; can use existing infrastructure at mine sites.	Cost effective if relatively high concentration of target metal/mineral; sulfuric acid leaching for base metals (e.g., Zn, Cu); cyanide, thiosulfate for Au leaching.
Magnetic and gravity/size separation	Separation of target minerals using differences in magnetic properties or density and particle size.	Not applicable to all or many minerals or metals.	Low use of toxic chemicals.	Potential for recovering Fe, Mn, Ti, Cr, Zn from tailings.
Pyrometallurgy	The partial or complete conversion of a mineral to its elemental or another chemical form by dry, high-temperature physio-chemical changes.	High energy use, transportation issues, possible proliferation of smelters, air quality impacts on local communities and workers, generation of large slag piles that can leach to downgradient water resources.	Proven technology.	Includes calcination, roasting, smelting, refining; can be applied to sulfides and oxides; Ni, Sn, Au.
Bioleaching	Microbes used to solubilize target metals from wastes	Process slower than certain hydrometallurgical methods such as acid leaching; large tanks usually required; must select appropriate microorganism/consortium; depending on the process, harmful acidic conditions can be generated.	Lower cost and energy use, lower environmental impacts because it is conducted under mild conditions and avoids the use of toxic chemicals, effective for low-grade sources.	Primarily used for sulfide minerals but also applied to red muds; more work needed on Li recovery using bioleaching, has been successfully applied to recover Co, Cu, and REEs from tailings.

Sources: [36,60,61].

A generalized flowsheet for tailings reprocessing is shown in Figure 3. The figure does not address the extensive site-specific characterization that is needed but provides a sense of the multitude of processing methods that can be used alone or in combination to extract metals from tailings. The inert waste in the diagram can be upcycled to produce secondary raw materials for the construction or ceramics industry (see, e.g., [36,62–65]) to improve circularity.

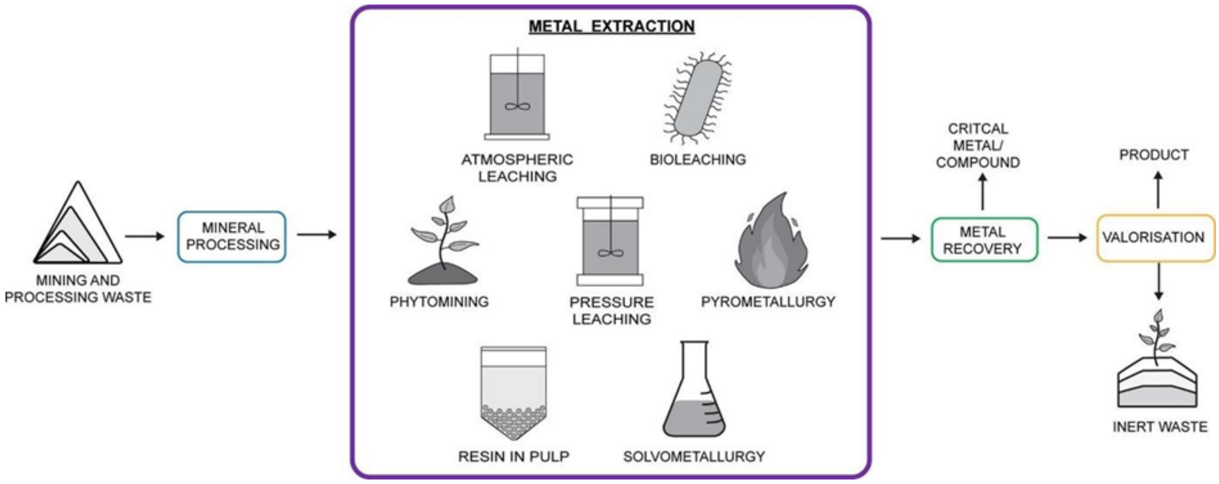

Figure 3. Generic flowsheet for tailings reprocessing. Source: [61]. Reprinted with permission from Elsevier.

A more detailed proposed flowsheet for the extraction of REEs from mine tailings at LKAB's Kiruna iron ore mine in Lapland, Sweden, the largest underground Fe ore mine in the world, is presented by Sarker et al. [60]. This approach holds promise because of the large amount of Fe ore tailings worldwide and the potential to extract important renewable energy metals from certain kinds of Fe ore wastes. The discovery of more than one million tonnes of REEs, confirmed using the 2021 PERC reporting standard [66], has been hailed as highly significant because Europe has no REE mines, and this project could supply a large part of the EU's future demand for manufacturing magnets needed for electric motors in EVs and wind turbines [67]. The one-million-tonne estimate appears to be for virgin extraction from a newly discovered deposit at the site. However, a study has been conducted on the extraction of REEs from existing tailings at the LKAB iron mine in Sweden [68], with claims that LKAB will be able to produce 30% of Europe's REE needs from mine waste [69].

Monazite and apatite, phosphate minerals that contain REEs (higher concentrations in monazite), are found in the Fe ore tailings, and are proposed to be separated from the tailings using flotation. The largely hydrometallurgical processing methods described by Sarker et al. [60] involve acid leaching, cryogenic crystallization, solvent extraction, precipitation and calcination, and molten salt electrolysis. The proposed process uses toxic chemicals, including nitric acid for acid leaching and kerosene for solvent extraction. "Greener" lixiviants, such as organic acids that more readily biodegrade, have also been examined for the recovery of copper and arsenic from mine tailings [70].

Machiels and Perumal [71] include several abstracts from the conference in Belgium that describe the application of different processing approaches for the extraction of critical minerals from wastes, including flotation and bioleaching. Other studies on bioleaching of metals and metalloids from tailings include those of Makinen et al. [72] (bioleaching of Co from pyrite-rich tailings), Cameron et al. [73] (bioleaching of Ni and Co from pyrrhotite-rich tailings), and Opara et al. [74] (bioleaching of metal(loids) from pyrite-rich tailings and waste rock). Falagan et al. [75] and Johnson [76] also discuss the prospects for the use of bioleaching and biotechnologies to extract metals from tailings, mine wastes, ores, and AMD in more detail. Of the examined processing approaches, bioleaching appears to offer the most benefits with the fewest potential downsides.

4.2.2. Reprocessing of Coal Ash and Extracting Value from AMD

Coal Ash

Coal ash is covered only briefly because of its different origin and processing method (burning of coal at power plants). However, it has garnered much attention lately as a widely available source of REEs, and many researchers have devoted efforts to developing effective processing methods. Acid drainage can be produced from coal mines located, for example, in Appalachia in the eastern United States, and from hardrock mines that have extracted ore from sulfide deposits. Extracting critical metals needed for the renewable energy transition from these sources has the added environmental benefit of remediating abandoned coal and hardrock mines by removing coal ash and coal waste piles and impoundments and capturing and treating AMD.

The target for coal ash and AMD reprocessing has overwhelmingly been the recovery of REEs. As noted in Section 4.1 and the examples in the Supplementary Materials, the recovery of Li and Co and other metals from coal wastes and coal mine drainage is also being investigated. The identity and distribution of REEs in coal mine vs. Cu mine acidic drainage (Berkeley pit lake in Montana, U.S.) are similar; in the samples examined, Y and Ce had the highest concentrations, followed by Nd [77].

AMD and Associated Sludge

Acid mine drainage is the most environmentally damaging water quality problem associated with metal mining, and it can require management and treatment in perpetuity. It has affected thousands of miles of streams across the United States, Europe, and Australia and created adverse impacts to aquatic life and stream habitat [78–81]. Finding a use for these mine-affected waters and sludges that could supply renewable energy metals would also benefit communities and environments through associated cleanups. The costs associated with transporting AMD and associated sludges to reprocessing plants or with building plants at or near existing locations with AMD, for example, will need to be factored into estimates of feasibility.

The U.S. Department of Energy's National Energy Technology Laboratory (NETL) Research and Innovation Center has produced a mixed rare earth oxide (MREO) with <95% purity (<950,000 ppm) from coal ash, AMD, and other wastes from legacy mining operations using physical and chemical separation and advanced sorbent materials [32]. West Virginia University in the U.S. has produced REE pre-concentrates from AMD and sludges from the Appalachian Coal Basin since 2018, and in 2020 they successfully produced ~98 wt.% (980,000 ppm) pure MREO concentrates from AMD with the co-production of other critical minerals [32].

Hassas et al. [82] used AMD samples and associated sludge from three streams in Pennsylvania, U.S., coal country. The sludge contained Co, Ni, Zn, S (as sulfate), Al, Mg, Ni, and Mn. The measured concentration of REEs in AMD samples increases dramatically at lower pH, ranging from ~0.01 ppb at neutral pH to 1000 ppb at pH values near and below 3. As has been found in other studies, the AMD samples had a high heavy:light REE ratio. The sludges form characteristically along streams draining coal and certain hardrock mining areas as stream pH values increase from dilution with less contaminated surface waters. Therefore, "mining" streambeds in affected areas is a potential way to recover REEs and remediate AMD-influenced streams, if proper environmental precautions are taken.

Sludges also form from the treatment of AMD via neutralization to higher pH values. The sludge contained substantially more REEs than the AMD. The process included a pre-treatment step (oxidation and Fe removal at pH 4), followed by a three-stage precipitation process that results in the precipitation of Al and REEs separately at pH 5 and 7 using sodium carbonate (the carbon footprint of the reagent should be estimated). The third stage used ammonium hydroxide and sodium hydroxide to precipitate Co and Mn at pH 9. Additional cleaner steps were developed to obtain high-purity products. The overall recovery was >99% for the target elements, and the recirculating load reduced the amount of water used in the process. In traditional AMD treatment, the pH is raised all at once and does not provide an opportunity for the separation of different metals at intervening pH values. Although the AMD sludges had higher concentrations of REEs and other metals, direct REE extraction from AMD eliminates the need for dissolving the sludge and results in lower reagent and processing costs and more sustainable waste disposal practices [83].

Hermassi et al. [84] examined the recovery of REEs from AMD using a three-stage process that separates REEs from other metals, including Fe, Al, Mn, Cd, and Pb, using iron precipitation, ion exchange, and precipitation with phosphate solutions. The concentrate produced is an REE-rich byproduct that is recovered as REE phosphates. The primary REEs recovered after pre-treatment and phosphate precipitation were Pr, Ce, La, and Y.

Simate and Ndlovu [85] examined the creation of useful products and applications from AMD, including Fe pigments, building and construction materials, and adsorbents in industrial wastewater treatment. The recovery of metals, water, and sulfuric acid and the simultaneous removal of metals from AMD, and the production of electricity using an AMD fuel cell, were also examined. Specific examples of commercially developed projects are included.

In general, the approaches examined for the processing of coal ash and AMD and sludges use actual samples from impoundments, streams, and treatment areas, but the work is at the bench and pilot scale rather than the commercial scale. The U.S. DOE is awarding a USD 140 million grant to create an REE demonstration facility using feedstock from AMD and mine wastes [86]. The presence of REEs and other metals needed for renewable energy technologies in these sources is promising, and more characterization and assessment will be needed to advance the efforts to larger scales.

4.3. Estimates of Processing Costs

The costs for the characterization and processing for recovery of metals from tailings must be considered when evaluating whether a remining project is economically viable. Two relevant studies have been conducted for the recovery of metals from Cu tailings in Chile. Marín et al. [46] examined processing costs for the recovery of Cu and V using dimensional and sensitivity analyses and production and water and energy consumption data from 48 large and medium-sized mines in Chile that represent 98% of Cu production in the country. Electricity and electricity consumption prices had the highest impact on total processing costs. They found that processing costs for recovery of V_2O_5 would be 6218 USD/tonne and for Cu would be 2953 USD/tonne using hydrometallurgical processes. These costs are 40.9 and 44.2% lower than operating costs for similar primary mining operations.

A single case study was conducted by Drobe et al. [87] on a Cu tailings impoundment in Chile that also contains magnetite. Characterization of the tailings impoundment included X-ray fluorescence and mineralogic analysis to a depth of up to 11 m below the surface. Flotation and conventional sulfuric acid leaching tests were performed to evaluate the extraction of sulfide and oxide minerals. Their preliminary results indicate that it would be difficult to reprocess Cu economically from small tailings impoundments. Assuming a capacity of 500 tonnes/d and using flotation for the recovery of Cu, the operational expenditure (opex) was estimated at 13.2 USD/tonne, which represents a reduction of 40% over primary mining; capital expenditure (capex) also showed a reduction of 50% using the same criteria.

Estimates of processing, characterization, and operating costs will vary widely for each mine waste deposit, location, grade, size, and other factors. These two studies provide examples of approaches and costs for the recovery of Cu from mining tailings in Chile, which is the largest Cu-producing country in the world and contains billions of tonnes of tailings (Cacciuttolo and Atencio [1]).

5. Environmental and Health Impacts

Examining and understanding the potential positive and negative effects of remining on the environment, ecological systems, communities, and workers is an information gap that needs to be filled as remining operations become more common. Because very few remining projects are currently operating at full commercial scale, the longer-term unintended consequences must be based on experience, observing the effects from mining and related industrial activities in general, and on limited information from previous or ongoing remining operations.

5.1. Potential Risks to the Environment and Human Health and Safety from Remining

5.1.1. Impacts from Virgin Extraction vs. Remining

Virgin mining is an industry that creates large amounts of waste for a relatively small amount of product and uses large amounts of water and energy in the extraction, concentrating, processing, and transport of mined materials. The adverse environmental effects of virgin extraction have been the topic of countless studies, articles, and many books (see, e.g., [2] for a review). Some of these impacts are impossible to avoid completely because of the large-scale nature of mining, but effective prevention and mitigation measures during all phases of mining can minimize, and in some cases eliminate, the adverse effects. Many of these consequences can result from remining operations (e.g., water quality impacts, tailings dam failures), but others are not possible, are unlikely to occur, or will be much lower at remining operations (e.g., landscape-level destruction from the creation of open pits, changes to stream flows and groundwater levels). More work is needed to better understand the potential environmental and human health impacts of remining over virgin extraction.

5.1.2. Impacts on Indigenous Communities

Owen et al. [88] examined the intersection of virgin extraction projects for renewable energy minerals and land-connected peoples (Indigenous and peasant) worldwide. They found that more than half of these projects are located on or near the lands of Indigenous and peasant peoples. The commodity with the highest percentage of Indigenous, peasant, or both communities is bauxite, and the commodity with the highest percentage of Indigenous only is lithium. Across all 17 primary commodities examined, the percentage of projects close to Indigenous, peasant, or both communities ranged from 68 to 94%. While the study only examined operating or planned virgin extraction projects, many of these projects hold remining potential now or in the future. The potential impacts of the remining projects, including impacts to important cultural and spiritual sites, must be evaluated, and free, prior, and informed consent (FPIC) must be gained from Indigenous communities before remining projects begin.

5.1.3. Tailings Dam Failures at Remining Operations

Tailings dam failures have recently caught the attention of the general public, due to some large-scale and fatal failures that occurred, primarily but not only in South America [25]. Tailings deposited in a saturated state, especially with a supernatant cover, are more likely to have serious adverse consequences. Two of the most common failure modes are overtopping related to a large precipitation or storm event and liquefaction related to earthquakes [25].

Remining operations can and have had tailings dam failures. For wet, slurried tailings in dammed impoundments, rehandling could result in a tailings dam failure if the original dam or a new dammed impoundment is not properly designed and managed and if removal is not planned and paced to avoid a breach. A fatal tailings dam failure occurred on 11 September 2022, at the Jagersfontein Mine in South Africa related to the recovery of diamonds by reprocessing of old diamond mine spoil heaps [25,89]. The January 2000 tailings dam failure in Baia Mare, Romania, resulted from the overtopping of a dam built to store cyanide leach tailings from the recovery of Au from old tailings [90]. The Baia Mare spill contaminated drinking water for more than 2 million people in Hungary [25].

The potential for a tailings dam failure as a result of remining should be evaluated and modeled and include the potential extent and effects on downstream communities; emergency planning measures should also be implemented [27,28]. In addition to environmental and human health effects from dam failures, the sampling of wet tailings as part of remining characterization, especially away from impoundment edges, could result in worker safety issues. If tailings require regrinding, more slimes will be produced that will be harder to dewater and manage. The smaller particles often contain higher metal concentrations [17], and releases from them could result in leaching of higher metal concentrations to the environment. The acid generation potential of the remined tailings should be evaluated as part of site characterization. Tailings with acid generation potential can release large amounts of acidic and toxic waters, such as those that occurred in the IPB in Spain in April and December 1998 [25].

Methods for draining water from tailings can be used to increase the stability of tailings impoundments and decrease the risk of tailings dam failures for wet impoundments. Cánovas et al. [56] compared the reduction of water in solid samples simulating tailings material with the variable percentages of fines and initial moisture contents using electroosmotic and gravitational drainage. The results showed that electroosmotic drainage is more efficient with more fine particles and is stimulated by a higher liquid content, suggesting that this technique could improve the stability of wet tailings impoundments and reduce the potential for tailings dam failures more effectively than gravitational drainage. Valenzuela et al. [91] conducted a very similar laboratory study, found similar results, and discussed their application to reducing the environmental liabilities of tailings impoundments.

5.1.4. Effects on Closure, Pollution Pathways, and Processing Facilities

Remining could be used as an excuse not to reclaim or close a mine. The concurrent reclamation and closure of completed mined areas should be applied as soon as possible. Evaluating the benefits of a combined remining and virgin extraction project would be difficult. Such projects could gain acceptance and permits based on the perceived benefits of remining, especially if critical minerals are the remining target. The LKAB mine in Sweden has remining and virgin extraction REE resources. The extent to which REEs would be extracted from virgin-mined Fe ore versus tailings at the LKAB mine in Sweden is not currently known. Expansion of the mine is expected to adversely impact Indigenous reindeer herders and the community in and around Kiruna [92]. In general, remining could provide a "foot in the door" to reopen the mine or explore for additional new deposits.

If the wastes targeted for remining have been dry and accumulated soluble metal-rich salts and are then wetted or exposed to rain or melting snow as part of the remining process, metals in the soluble salts can be flushed to downgradient groundwater and surface water resources [93–95]. Blengini et al. [51] note that opening historical waste sites for recovery can create risks due to the reactivation of pollution sources and pathways.

Because moving reactive wastes can redissolve readily soluble salts, create dust, and allow metal-rich particles to escape from the waste facilities, there could be an initial increase in air and water pollution that would diminish relatively quickly if appropriate and safe remining approaches are used. Careful environmental baseline/background studies are needed to characterize environmental conditions, including groundwater and surface water quality, air quality, and land usability, before and after remining occurs.

If remined concentrates need pyrometallurgical processing, additional smelters could be needed, or closed smelters could be reopened, potentially resulting in increased toxic air emissions. Transportation (increased truck traffic), noise, and prolonged community exposure to wastes are additional negative environmental impacts that could result from remining operations.

After remining is completed, a large waste stream could remain. The remaining wastes must either be disposed of in a more environmentally secure manner or examined for their use as construction or other materials that would minimize the amount of wastes remaining on site. The best available technology (BAT) for the disposal of any remaining tailings and other mine wastes should be used. Although some contaminants are removed from wastes as part of the remining process, the disposal of remined tailings could result in long-term leaching, and liners, leak detection systems, and covers will be needed to minimize downgradient contamination [96].

Despite these and other potential and realized risks from remining, important environmental, social, and economic benefits can accrue from properly conducted operations.

5.2. Potential Environmental Benefits of Remining

Many articles cite the general environmental benefits of remining, but little information is available on the positive effects using actual measurements before and after remining has been conducted. The benefits of remining must accrue from the carefully planned and executed characterization, rehandling, and processing of the source materials.

5.2.1. Cleanup of Abandoned Mines

The potential environmental benefits of remining are perhaps highest when wastes are removed and reprocessed from abandoned sites [77,83,97]. In the United States, coal mining has addressed the remediation of its surface mines through funded programs, whereas hardrock (metal) mining has only recently secured limited federal funding (5 million USD in FY23 through the Infrastructure Investment and Jobs Act) to clean up the approximately 500,000 legacy and abandoned sites across the United States [98,99].

The cleanup of abandoned and older mines as part of remining can remove uncontrolled and perpetual sources of pollution and help return the land and water to beneficial use. The removal of mine wastes at the many mining Superfund sites in the United States has resulted in improved environmental conditions and improved land uses (see, e.g., [100] for removal actions at mining sites in the western United States). Improved water uses (e.g., drinking water, the protection of aquatic life) and habitat quality can result from the careful removal, remediation, and reprocessing of mine waste sources.

Although remining has not yet been an important part of abandoned mine cleanups in the United States, the potential for combining the cleanup of abandoned coal and hardrock mine sites with remining could help fund cleanup operations. If remining is part of the solution for the cleanup of abandoned coal or hardrock mines, comprehensive evaluations, such as those required for Environmental Impact Statements (EISs), should be required. Transparency and public review should always be a part of a remining assessment.

5.2.2. Lower Energy and Water Use

Comminution, the crushing and grinding of mined ore, uses by far the most energy in mining, accounting for 3% of all electrical power generated in the world [101]. Although some additional grinding may be required, the remining of material that has already been crushed, ground, and/or processed (e.g., tailings, smelter slag, coal ash, red mud) as the source materials for renewable energy metals should result in a large reduction in greenhouse gas (GHG) emissions compared to virgin extraction, assuming non-fossil-fuel energy sources are used for remining operations. Little information is available on water use in remining operations, and best practice and regulations should include a careful accounting of water use. The remining of wet tailings and red mud can create an opportunity for the reuse of entrained water after water treatment, its delivery to local communities, and lower potential for tailings dam failures [60]. The processing of mine wastes that contain acid-generating sulfide minerals with metals of interest for renewable energy can lower the acid generation potential at the site and improve downgradient water quality conditions [82,83,85,102].

5.2.3. Improved Circularity

If conducted using the best available technology and practices, the removal of risky tailings facilities as part of a remining process can result in multiple environmental and social benefits, including reduced exposure to tailings dam failures; reduced risks to scarce water, aquatic ecosystems, and drinking water; reduced risk to ecosystems, aesthetically valuable lands and recreational areas, reduced biodiversity risk; reduced social tensions due to land use conflicts; and reduced risks to human health and from social unrest [103]. Another potential benefit of remining is improvements in the circularity of mine wastes via the creation of usable products and minimization of the amount of waste remaining after remining is conducted. A detailed study examined the leachability of certain metals and metalloids after original and remined sulfidic wastes (using bioleaching or flotation) and in products created from the post-remining wastes [104]. The original mine waste contained high levels of Pb, Zn, and As, and the remining methods did not always lower these concentrations. The construction and ceramic materials created from the post-remining wastes generally decreased the mobility of the metal(loid)s, especially when longer curing times or higher firing temperatures were used. However, arsenic concentrations increased in some cases. These kinds of studies are needed to determine the viability of improving the circularity of remining operation by creating safe and usable post-remining products.

One of the challenges in reprocessing tailings is the presence of water in slurry-deposited tailings. An approach that aims to improve the circularity of tailings reprocessing is shown in Figure 4. The saturated tailings are first thickened to create drier, filtered tailings. Wastewater produced from the thickener and the filtration process could be treated using a mine water treatment technology called Virtual Curtain or more conventional methods such as nanofiltration and reverse osmosis membrane technologies. The Virtual Curtain technology was developed by CSIRO and uses hydrotalcites (a magnesium carbonate clay mineral used in stomach antacids) to purify the water without requiring complex infrastructure or harmful chemicals; it produces less sludge than conventional lime treatment and creates a solid product with metal recovery potential [105,106]. The filtered tailings can then be processed using bioleaching. Electroosmotic drainage can also be used to drain wet tailings impoundments and create an opportunity for the recovery of water and metals [56,91]. A large tailings deposit could still exist after remining. An evaluation of potential uses for the post-remining waste could be further carried out to improve circularity.

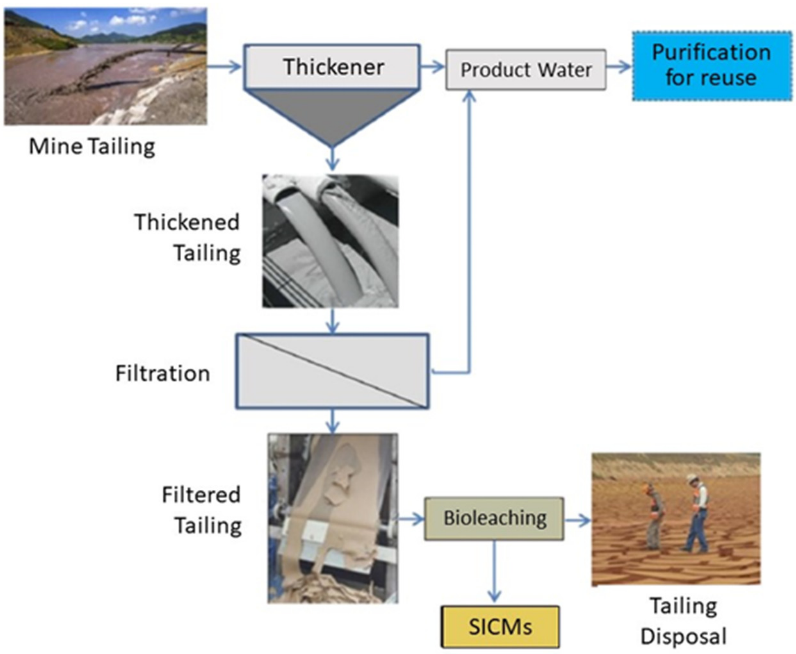

Figure 4. Integrated recovery of strategically important critical minerals (SICMs) from saturated mine tailings. Source: [60], modified from Figure 4. Reprinted with permission from Elsevier.

Given the potential and realized adverse environmental consequences of remining and the general lack of specificity and examples of positive impacts, additional studies, best practices, and regulatory requirements are needed to better understand the benefits and risks of remining operations.

5.3. Tools in Use, Proposed, or Needed to Address Remining Risks

5.3.1. Best Practices

Currently, no best practices exist specifically for remining operations, including those related to characterization, handling, environmental effects, the protection of cultural and spiritual uses and sites, human and ecological health, worker safety, or economic assessment. U.S. EPA [107] published a best practices document for the remining of abandoned coal mines, but the focus was on characterization for pollution and the minimization of pollution from coal spoils. Many of the best practices related to virgin mining can be applied to remining operations. The European Commission released a BAT reference document for the management of extractive wastes in 2018, abbreviated as MWEI BREF [108]. While its focus is on virgin extraction and associated waste management, several approaches and conclusions are relevant for remining, including corporate management, data management, and minimizing water, air, and soil pollution. Blengini et al. [51] and Maraboutis et al. [109] discuss the application of MWEI BREF to the recovery of critical and other raw materials and to the circular economy. While the MWEI BREF includes measures to prevent the adverse effects of mining operations, its BAT for waste characterization is not sufficient to determine the economic potential or recoverability of metals from remined wastes.

Examples of best practices in mining are available through the Initiative for Responsible Mining Assurance (IRMA) [110]; the IRMA Standard is currently being revised and updated). A thorough site characterization is needed to determine and understand environmental, ecological, community, and other relevant conditions before remining begins. Baseline monitoring should be conducted for at least two years, unless comprehensive monitoring has been ongoing at the site for years. The Yukon Government in Canada requires at least three years of baseline/background water quality data to support the development of water quality objectives [111]. The emphasis should be on conditions in, around, and downgradient/downwind of the areas where wastes will be disturbed for remining. An accounting of the chemicals used for remining and their toxicological properties must also be conducted. Projected water and energy use and GHG emissions should be estimated over the life of the project, including during closure and post-closure. The transport of wastes on and off the site will need to be accounted for in terms of costs, GHG emissions, noise pollution, and other factors. Many of these evaluations are required for ESIAs, and remining projects should be subjected to these assessments whether or not they are on federal lands or have planned discharges to water resources.

Remining should not be conducted under the same mining permit or license used for the mine, if such a license exists (i.e., if not an abandoned site). A new assessment should be conducted to evaluate the economic potential and the potential environmental, physical stability, safety, and human health consequences of the remining project. The remining project should be subject to financial assurance requirements, and an emergency response plan should be designed, in collaboration with local stakeholders, especially for operations that source tailings from wet, dammed impoundments or that use wet deposition in dammed impoundments for the wastes remaining after remining. Financial assurance estimates and emergency response plans should be regularly updated.

The United Nations Framework Classification of Resources (UNFC) applies to natural resource extraction from fossil fuels, nuclear, mining, and renewable energy sources and assesses projects based on environmental–socio-economic viability, technical feasibility, and degree of confidence [112]. Such an approach is not currently required for remining projects but could be applied early in the project history to determine if additional evaluations are warranted (see, e.g., [113]).

Suppes and Heuss-Aßbichler [103] devised an approach to systematically screen tailings storage facilities for remining based on the contents, physical structure, surroundings, potential environmental and social impacts, and potentially affected stakeholders. Their approach is compliant with the UNFC [113,114]. A previous article by the same authors [103] describes how to develop a remining project from the first on-site exploration to deciding whether to intensify exploration and development.

5.3.2. Community Engagement

Engagement with potentially affected communities should begin when the remining project is identified (see Figure 1). One remining project (Cerro de Pasco, Peru) mentions engagement with the local community. One of the AMD remining projects [77] discusses environmental justice issues related to virgin coal extraction and marginalized communities around coal mines in Appalachia, Pennsylvania, U.S. This project also involved local communities in the development of the remining projects to protect their interests and the environment and mentions economic advantages, including the creation of jobs for local communities and improved opportunities for economic development (see Supplementary Materials).

5.3.3. Regulatory and Life Cycle Assessments

Regulatory assessments such as EISs contain information on economic value and the potential adverse effects of developing the deposits, and an evaluation of alternative development approaches. The Golden Sunlight Mine in Montana, U.S., produced an EIS for the remining of tailings [102].

The only U.S. EIS that is solely for a remining project is for reprocessing Au tailings at the Golden Sunlight Mine in Montana, U.S., owned by Barrick Gold [102]. The mine closed in 2019 after producing more than 3 million ounces of Au over a 40-year period and is known for its extensive AMD problems, which will be partially addressed by removing sulfides as part of remining. The project aims to eliminate the need for perpetual water treatment and to reprocess their tailings and sulfide tailings from nearby mines using flotation. The tailings contain S, Au, Fe, Cu, and Ag. The existing mill and ancillary building will be repurposed, and the Au and Ag will provide an additional economic benefit. The reprocessed waste tailings are planned to be deposited in the existing Mineral Hill open pit. Public review of the remining plan did not reveal any objections from environmental community reviewers. In addition to reducing AMD, the additional employment will include 20 on the mine site, 10 for a local mining contractor, and additional drivers.

The environmental consequences of developing the remining project on water resources, soils, vegetation, wildlife, land use and recreation, and visual resources were evaluated in the EIS. Socioeconomic, noise, and cumulative impacts were also evaluated. The Golden Sunlight Mining remining EIS is a good example of the type of analysis that should go into all remining projects.

To my knowledge, no life cycle assessments of remining projects have been conducted that consider environmental, social, and economic effects, but two studies are directly or indirectly applicable to remining.

A life cycle impact assessment (LCIA) of sulfidic Cu tailings was conducted for 431 active Cu mines around the world [115]. The environmental impacts of existing Cu tailings, rather than those related to remining or reprocessing of the tailings, were evaluated. The assessment shows the potential adverse environmental effects of existing Cu tailings on freshwater ecotoxicity and the leaching of tailings contaminants to groundwater and other natural resources. The LCIA used information on the type of ore body mined and local hydrometeorological information to determine relative infiltration and leaching scenarios and emphasizes the importance of using site-specific information. Their approach can serve as a screening tool to prioritize sites for remediation, reprocessing, and valorization of mine tailings.

A screening-level LCA was conducted for the beneficiation of REEs from two tailings facilities in Sweden and Portugal [116]. The most detrimental environmental effect for the New Kankberg Au tailings (Sweden) was from the disposal of the final residues after beneficiation. For the Covas tailings (Portugal; from underground tungsten mining), the highest environmental impact was from electricity consumption (use of fossil fuels) for gravity and magnetic separation. The use of renewable energy sources for the processes would improve the outcome of the LCA. Although positive environmental effects resulted from removing the old tailings, the negative effect of land disposal of the tailings after beneficiation essentially balanced out the positive impacts.

6. Summary Discussion and Conclusions

The increasing demand for critical minerals and metals needed to address the climate crisis, the enormous quantity of mine waste around the world, and the existing characterization results for metals of great interest to society in mine wastes all strongly suggest that remining is a feasible and desirable way to help supply these metals. At this point, characterization data are sorely lacking to make quantitative estimates of the recovery potential of remining sources for renewable energy metals. Consequently, the potential for remining to compete with or supplement virgin mineral extraction or mineral recycling is unknown.

6.1. Summary Discussion

Table 5 summarizes the advantages and challenges associated with the recovery of renewable energy metals from mine waste sources. The primary metals targeted are listed in alphabetical order by their chemical abbreviations and are based on information provided in Sections 4 and 5. The advantages for all remined sources include an increased domestic supply, especially of REEs; generally lower energy and water use; potential for the cleanup of abandoned mine lands and mine-affected waters; and increased local employment. Some common challenges include a lack of comprehensive sampling and characterization information, the evaluations that are needed to provide increasing circularity by creating products from the post-remining wastes, and the evaluation of potential positive and adverse environmental outcomes.

Based on the pros and cons outlined in Table 5, at this point it appears that tailings hold the most promise for remining because of the relatively large number of metal extraction studies conducted on tailings, the large amount of tailings worldwide, and the fact that they are already extracted and pre-processed, which reduces energy and potentially water use. One of the greatest threats from remining, however, stems from the rehandling of wet tailings in dammed impoundments. With more waste characterization and pilot projects, the potential for the recovery of renewable energy metals from all remined sources can be better evaluated. Of the processing approaches examined for recovery from tailings, bioleaching appears to offer the most benefits with the fewest potential downsides.

6.2. Recommendations and Future Directions

The following conclusions and recommendations aim to improve the future knowledge base about remining's potential and provide additional data, transparency, and information about the potential environmental effects.

To improve the reliability and understanding of remining's potential:

- More and better characterization of waste source materials is needed, including mineralogy and metallurgical evaluations such as mineral liberation. Improved estimates of resources and reserves are needed for mining wastes based on improved characterization and economic and environmental assessments.
- Improvements in sampling approaches, especially for wet tailings, are needed.
- More work is needed on the potential for extraction of lithium and rare earth metals from mine wastes, especially tailings.
- Full circularity examples and plans are needed to evaluate the potential to more fully reclaim and make use of the wastes remaining after remining.
- Best practices for remining, from exploration through to final disposal or reuse, are needed.

Table 5. Advantages and challenges for the recovery of renewable energy metals from remined sources.

Remined Source	Primary Targeted Metals	Advantages	Challenges
Tailings	Ag, Cd, Co, Cu, Ga, Li, Mn, Ni, (Au), REEs	Already crushed/ground; lower energy use and GHG emissions compared to virgin extraction; can often be reprocessed on or near mine sites using existing infrastructure; amenable to bioleaching, which uses few toxic chemicals.	If regrinding is needed, this will produce slimes that present management challenges and limit floatability; detailed characterization to estimate economic value and environmental effects generally lacking; tailings dam failures have resulted from remining, and careful evaluation is needed to lower failure risks.
Waste rock	Cu, Li, Zn	Can have higher metal concentrations than tailings due to varying ore cut-off grades over time.	Generally not in contained impoundments; highly variable chemistry and particle sizes; access issues if co-disposed with tailings.
Bauxite residue/red mud	Al, Cr, Ga, REEs	Potential for removing enormous waste piles that pose environmental and human health and safety risks; increased domestic supply.	Reasonable management and circularity options for remaining wastes not examined; remining of wet tailings could result in dam failures if not carefully conducted.
AMD discharge and sludge	Co, Mn, REEs	Direct extraction from AMD eliminates the need for dissolving the sludge and results in lower reagent and processing costs and more sustainable waste disposal practices; domestic REE source; remediation of abandoned mine lands/affected waters.	Processing facilities will need to be built nearby and will likely require the collection and transport of AMD and associated sludges.
Secondary recovery from ore production byproducts	Li, Te	Work so far by mining companies has shown potential for two metals in low supply relative to demand; domestic sources of Li and Te.	More work needed by mining companies on potential for secondary recovery in terms of available waste quantities and metal content.
Coal ash	Co, Mn, REEs	Potential for removing and/or making use of waste in large impoundments that pose environmental/human safety risks; domestic supply.	Transport likely needed; strong chemicals generally needed for reprocessing; full circularity (using remaining wastes) not evaluated.

To improve transparency and data availability and to understand the potential positive and negative consequences of remining:

- More work is needed to predict, understand, and prevent the potential adverse effects of remining on the environment, ecological systems, communities, and workers. Water and energy use and GHG emissions should be estimated and reported for all remining operations.
- Although the potential positive effects of remining are often cited in the literature, few studies have attempted to quantify those effects. Careful baseline/background studies are needed to characterize environmental conditions before and after remining occurs.
- Life cycle impact assessments and other studies comparing energy and water use and environmental, social, and economic effects for virgin extraction versus remining operations would help to understand the advantages and drawbacks of remining.

- Remining should not proceed under the same license or permit used for virgin extraction at the same site. Financial assurance and emergency response plans should be developed in collaboration with local stakeholders and updated regularly.
- Due to the close association between renewable energy projects and Indigenous and peasant communities worldwide, the potential impacts of the remining projects must be evaluated, and free, prior, and informed consent must be gained before projects begin.
- The use of renewable energy sources for remining operations and related transportation will reduce GHG emissions associated with the projects.
- Adding traceability of remined metals and created products would allow for credit as "green" metals, if strict criteria are met.
- Improved accountability is needed by using EISs, NI 43-101 reports, and preliminary economic assessments as public-facing documents with adequate public review.
- The U.S. Toxics Release Inventory (TRI) and other pollution reporting registries have not been designed to collect data that can be used to estimate remining potential. Needed improvements include identifying the waste sources (e.g., tailings, waste rock); the total volume and mass of waste and percent of metals of interest (to allow for estimates of grade); basic metallurgical evaluation of wastes, especially mineral liberation and potential processing methods; and expanding the metal list to include Li, REEs, Al, Fe, and Zn (as metal releases to land and water), and other metals currently not included that are important for achieving renewable energy goals. The E-PRTR should include similar reporting requirements and expand its reporting of releases to land to facilitate estimates of metal recovery from tailings and other land-disposed mine wastes.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/min13111454/s1, (1) Examples of Remining Operations, Investigations, and Companies (ReminingExamples_final.pdf). (2) TRI.USGS.data_Table.3.xlsx. References [117–133] are cited in the Supplementary Materials.

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