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Remining and Restoring Abandoned US Mining Sites: The Case for Materials Needed for Zero-Carbon Transition

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Nuclear Energy and Fuel Cycle Division

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ABSTRACT

The electricity generation sector is responsible for 25% of the world's greenhouse gas (GHG) emissions and thus has been the focus of efforts to transition to clean energy and sustainable development in many nations. In the past 20 years, renewable energy sources have been the fastest-growing energy source in the world, comprising almost 29% of the world's electricity generation in 2020. Renewable energy sources are expected to comprise nearly 95% of the world's power capacity growth through 2026, with a share of planned capacity expansion of up to 46% in 2026.

The rapid development of renewable energy sources and technologies will require an enormous amount of raw materials to replace coal and gas plants and increase in the capacity to handle growing electricity demand because renewable energy sources have a low-power density and intermittent behavior. Accounting for the expected scale of rapidly deploying renewable energy sources that require rare earth elements (REEs), cement, and steel, the mining industry may face a supply problem for the materials critical for clean energy. And, as the exploration and development of new mining sites can be expensive and risky, the mining industry may require economic stimuli to grow supply.

The increasing demand for renewable energy resources makes mining a threat to the environment unless proper regulations are established and calls for remining, cleanup, and circular economic development are made. Mining also contributes to environmental injustices related to the exploitation and pollution of lands near communities that are dependent on biodiversity in the area, while not always benefiting from technological advancements provided by the use of renewable energy and technologies.

This study explored the opportunity of remining abandoned mining waste to extract metals and minerals essential for the production of renewable energy sources. The authors analyzed materials used in the production of these technologies, materials readily available in the United States, and which materials can be extracted locally in the United States from abandoned mine waste. The authors also studied environmental injustices that populations near mining sites experience and ways to mitigate these injustices, such as providing more control over extraction and cleanup activities, providing more job opportunities in those areas, and offsetting costs associated with cleanup and land restoration projects.

1 INTRODUCTION

Because over 60% of electricity is produced using fossil fuels, rapid decarbonization is difficult to achieve without a significant change in how electricity is generated and distributed. This leads to constant increases in greenhouse gas (GHG) emissions as electricity and economic growth, better health care, and access to education are provided to more populations and geographies (Zhang et al. 2019), increasing energy demand. In the past 20 years, renewable energy sources have been the fastest-growing energy source in the world (Apergis and Payne 2012). Renewable energy sources comprised almost 29% of the world's electricity generation in 2020 (Iea 2020) and are expected to comprise nearly 95% of the world's power capacity growth through 2026, with a projected share of the electricity generation portfolio being 46% by 2026 with solar photovoltaics comprising more than half of that share. Between 2021 and 2026, the amount of renewable capacity added is expected to be 50% higher than between 2015 and 2020 ("Renewable Electricity Growth Is Accelerating Faster than Ever Worldwide, Supporting the Emergence of the New Global Energy Economy"). The recent Bipartisan Infrastructure Law ("President Biden's Bipartisan Infrastructure Law" 2021) showed that the United States is willing to reduce the environmental impacts of GHG emissions and slow global climate change.

The rapid development of renewable energy sources and the technologies needed to build these systems will require an enormous amount of raw materials. The power density, or a surface area required to produce power, of renewable sources is much lower than that of coal or gas. For example, wind and solar have power densities of 1.84 W/m^2 and 6.7 W/m^2, respectively, whereas natural gas and coal have a power density of 240 W/m^2 and 135 W/m^2, respectively (Van Zalk et al. 2018). Thus, replacing these systems may require more raw materials to build renewable energy systems (Bauer et al. 2015; International Atomic Energy Agency 1996; Dunn et al. 2015; Giurco et al. 2019). Accounting for the expected scale of rapid deployment of renewable energy sources that require rare earth elements (REE), cement, Cu, Cr, Zn, and steel, the mining sector must keep up with the supply of these materials.

These demand changes and the lack of alternative supply mechanisms such as reprocessing and remining have geopolitical influence, leading to unpredictable price changes controlled by countries that own more technology-specific resources, such as REEs and the ability to process them from ore. Dependence on the centralized export of materials needed for renewable energy sources threatens energy security and diversity in countries that do not possess technology-specific materials. Despite the massive outsourcing of mining to other countries, countries such as the United States have thousands of abandoned mining sites with mining waste that still contain valuable minerals and metals whose extraction was not economical previously (Sim et al. 2014; "Rare Earth Elements Project Receives Federal Funding" n.d., "International Mine Water Association" 2002). These mines could be used again with newer technologies to extract valuable materials from mining waste rock, tailings, and landfills.

The mining sector is also responsible for 8% of total GHG emissions. The increasing demand for a growing capacity of renewable energy resources makes mining a threat to the environment unless proper regulations are established and calls for remining, cleanup, and circular economic development (Sonter et al. 2020; Navarro et al. 2008). The effects of increasing demand are worst in developing countries, such as Chile, China, and Peru, whose economies are dependent on commodity exports. Countries such as these are leading producers of metals and minerals and have less stringent environmental and public health protection regulations. These factors will greatly exacerbate the environmental injustices in both developing countries while they are not always beneficiaries of the technologies they provide materials for.

This study explored the opportunity of remining abandoned mining waste to extract metals and minerals essential for producing renewable energy systems. These abandoned mining sites can be used again with newer technologies to extract valuable materials from mining waste rock, tailings, and landfills, especially with the economic stimulus provided by growing material demand. The authors analyzed the materials used to produce these technologies, the materials readily available in the United States, and which materials can be extracted locally in the United States to avoid dependence on imports.

Remining activities may provide the first stage of cleaning up abandoned mines, offsetting some of the costs required for cleanup, providing jobs and infrastructure to a local population, and providing control over remining and cleanup activities to local communities who will be affected by either a lack of cleanup or benefit from access to new resources. Providing these choices to local communities will ensure just distribution and control of resources by the communities most impacted by mining activities, restore the sites, and provide control over the sites to local communities.

2 IN-DEMAND MATERIALS FOR LOCAL RENEWABLE ENERGY PRODUCTION

According to the International Energy Agency (IEA), the United States is expected to increase its electricity generation and grow its renewable energy capacity in the coming decades. As a result, coal usage will be significantly reduced to lower emissions (Figure 1), and solar and wind usage will significantly increase. Development of renewable energy technologies and infrastructure to support these systems (e.g., new transmissions, storage) are already changing material demand patterns ("Clean Energy Demand for Critical Minerals Set to Soar as the World Pursues Net Zero Goals"). Because most GHG emissions from renewable technologies are embodied in infrastructure (up to 99% for photovoltaics), there could be wide variations in life cycle impacts, depending on the source of the raw materials, their origins (e.g., mining sites), the mix of energy used in production, the mode of transportation used at different stages of manufacturing and installation, etc (Figure 2). These variations refer to the embodied impact, or the energy and emissions (e.g., CO_2), released to create, manufacture, transport, use, and dispose of each technology. The final life cycle assessment score, which may be lowered significantly if the infrastructure is more durable than anticipated, depends greatly on the load factor and expected equipment lifetime because impacts are embodied in the capital costs (UN Economic Commission For Europe 2022). Their embedded impact must be lessened by recycling used materials and reusing supporting structures (e.g., cement foundations, Al frames, etc), local mining, and reviving abandoned mines to extract necessary materials; embedded carbon emissions cannot be changed once a project is built, unlike operational carbon emissions, which can be reduced over time with technological advancements. To reduce the embedded carbon, researchers must implement the following methods.

- **Reuse:** Use materials that can be reused (e.g., concrete foundations, frames, steel elements); use recycled materials and design modular components for future recycling; and recycle mining waste before spending resources on a cleanup effort.
- **Reduce:** Perform material optimization and the specification of low- to zero-carbon materials.
- **Repurpose:** Repurpose sites that are no longer suitable for resident use; recycled mining sites can be suitable for this purpose.
- **Produce:** Produce locally, avoid outsourcing carbon emissions for mining activities to other countries, and be accountable for the waste generated in process and cleanup activities.

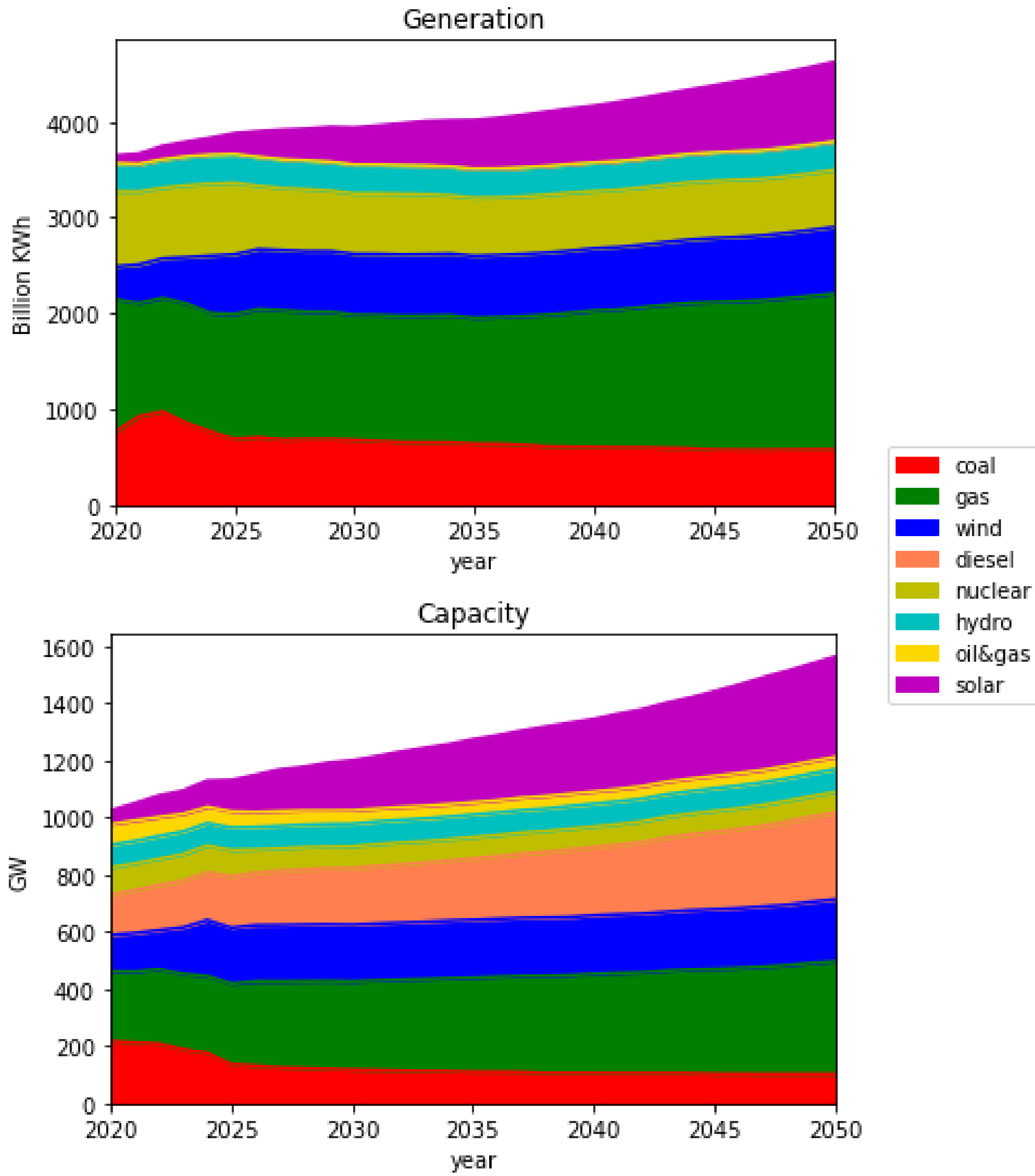

Figure 1. Estimated electricity generation and capacity changes in the United States from 2021 to 2050 (Energy Information Administration).

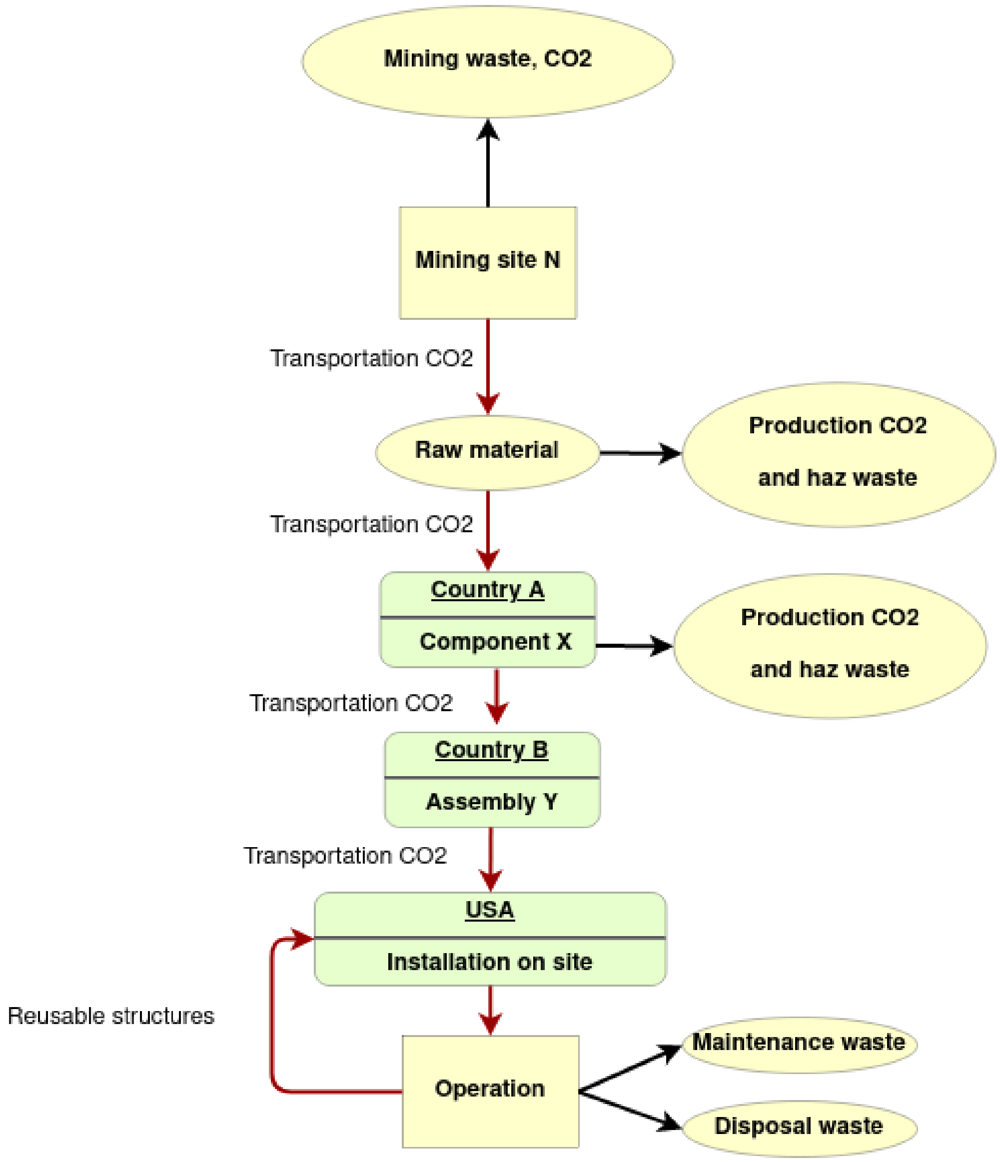

Figure 2. Example of renewable energy life cycle.

In a low-carbon future, it is anticipated that less coal and gas will be extracted but that the demand for more than 20 energy transition metals—including Fe, Cu, Al, Ni, Li, Co, Pt, Ag, crushed rock, cement, and rare earth metals—will increase (Lèbre et al. 2020; Ballinger et al. 2019). Although Fe, crushed rock, cement, and Cu are abundant and their production is well established inside the United States, other important materials are primarily imported, which poses a serious energy security threat and a threat to sustainable energy transition goals. To alleviate this threat, the United States must have alternative supply solutions within the country.

This report focuses on the materials needed and the potential to extract these materials in the United States by recycling abandoned mining waste. Abandoned mines could become a source for some technology-specific and economically valuable materials. Tables 1–3 show the material demand, what is currently recycled, what structures can sustain multiple life cycles, and the mining waste generated from renewable energy sources, such as wind, crystalline Si (c-Si) solar, and hydroelectric in the case of the raw material extracted from a pristine mining ore. The amount of mining waste can reach several million tons per megawatt of added capacity and pounds per megawatt hours generated (Figure 3) if pristine mining ore is used, especially if the mining occurs at a different location without using different processing streams to also extract byproducts.

Table 1. Raw material demand and mining waste generation to build a solar farm.

Material	Amount (kg/MW)	Ore fraction	Mining waste (kg/MW)	Recycling and reusing factors	Source
Silica	7,000	Ore grade about 35% and 50% of Si goes into waste during manufacturing	33,000	0	(DoE 2015)
Al	19,000	30%	44,333.3	0.76	(Schwarz 2004; Agency 2019; "International Aluminium Institute Publishes Global Recycling Data" n.d.)
Concrete	47,000	67% for cement, and concrete contains 21% of cement, sand, gravel, and water	6,612.9	1	(Elchalakani, Aly, and Abu-Aisheh 2014; Agency 2019)
Glass	70,000	35%	130,000	0	(DoE 2015)
Cu	7,000	2%	343,000	0.6	(DoE 2015; Soares 2022)
Steel	56,000	65%	30,153.85	0	(DoE 2015; Muwanguzi et al. 2012)
Ge	440	0.015%	1,099,560	0	(DoE 2015; U. s. Government Printing Office 2011)
In	380	0.01%	3,799,620	0	(DoE 2015; Grandell and Höök 2015)
Plastic	6,000	-	-	0	(DoE 2015)
Pb	2.4	1.732%	136.17	0	(Matasci 2021; Ponikvar and Goodwin 2013; Fraunhofer 2017)
Polyamide injection molded	485	-	-	0	(Mason et al. 2006; Moore, Post, and Mysak, n.d.)
Polyester	300	-	-	0	(Mason et al. 2006; Moore, Post, and Mysak, n.d.)
Polyethylene, Hd	150	-	-	0	(Mason et al. 2006; Moore, Post, and Mysak, n.d.)
Vegetable oil	6,001	-	-	0	(Mason et al. 2006; Moore, Post, and Mysak, n.d.)
Sn	463.1	50%	463.1	0	(Huber and Steininger 2022; Barry 2017)
		Total mining waste	5,486,879.32		

Table 2. Raw material demand and mining waste generation to build wind turbines.

Material	Amount (kg/MW)	Ore fraction	Mining waste (kg/MW)	Recycling and reusing factors	Source
Al	8,026.8	30%	18,729.2	0.76	(Alsaleh and Sattler 2019)
Brass Cu	52.3776	2%	2,566.5	0	(Alsaleh and Sattler 2019)
Brass Zn	26.2	3%	847.13	0	(Richards 2019)
Cast iron	47,350.4	65%	25,496.37	1	(Alsaleh and Sattler 2019)
Concrete	2,246,400	67% for cement, and concrete contains 21% of cement, sand, gravel, and water	316,068.48	1	(Alsaleh and Sattler 2019)
Cu	5,568	2%	272,832	0.6	(Alsaleh and Sattler 2019)
Fiberglass	3,490.8	-	-	0	(Alsaleh and Sattler 2019)
Steel	540,710	65%	291,151.54	1	(Alsaleh and Sattler 2019)
Lubricant	3,304	-	-	0	(Alsaleh and Sattler 2019)
Paint	1,311.12	-	-	0	(Alsaleh and Sattler 2019)
Polyethylene	329.4	-	-	0	(Alsaleh and Sattler 2019)
Polymer	5,888	-	-	0	(Alsaleh and Sattler 2019)
Porcelain	104.98	-	-	0	(Alsaleh and Sattler 2019)
Nd	216	5%	4,104	0	(Wilburn 2011; Gschneidner, Jr., and Pecharsky 2019; Dias et al. 2021)
Pr	40	5%	760	0	(Gschneidner, Jr., and Pecharsky 2019; International Energy Agency 2021)
Tb	5	5%	95	0	(Gschneidner, Jr., and Pecharsky 2019; International Energy Agency 2021)
Dy	17	5%	323	0	(Gschneidner, Jr., and Pecharsky

					2019; Huber and Steininger 2022)
Cr	902	31%	2,024.67	0	(Samuel Carrara, Patricia Alves Dias, Beatrice Plazzotta, Claudiu Pavel 2020; Moss et al; Downing and Bacon 2013)
Mn	80.5	35%	149.5	0	(Samuel Carrara, Patricia Alves Dias, Beatrice Plazzotta, Claudiu Pavel 2020; Moss et al; Downing 2013)
Mo	136.6	0.50%	27,183.4	0	(Samuel Carrara, Patricia Alves Dias, Beatrice Plazzotta, Claudiu Pavel 2020; Moss et al; Sutulov and Wang 2018)
Ni	663.4	9%	6,707.71	0	(Samuel Carrara, Patricia Alves Dias, Beatrice Plazzotta, Claudiu Pavel 2020; Moss et al; Verma, Paul, and Haque 2022; Wise and Taylor 2013)
		Total mining waste	969,038.5		

Table 3. Raw material demand and mining waste generation to build a hydroelectric plant.

Material	Amount (kg/MW)	Ore fraction	Mining waste (kg/MW)	Recycling and reusing factors	Source
Al	1,585.2096	0.3	3,698.8224	0.76	(Eckermann 2021)
Concrete	7,644,000	67% for cement, and concrete contains 21% of cement, sand, gravel, and water	1,075,510.8	-	(Pacca and Horvath 2002)
Cu	874.5984	0.02	42,855.3216	0.6	(Eckermann 2021)
Fe	60,128.64	0.65	32,376.96	-	(Pacca and Horvath 2002)
		Total mining waste	1,154,441.904		

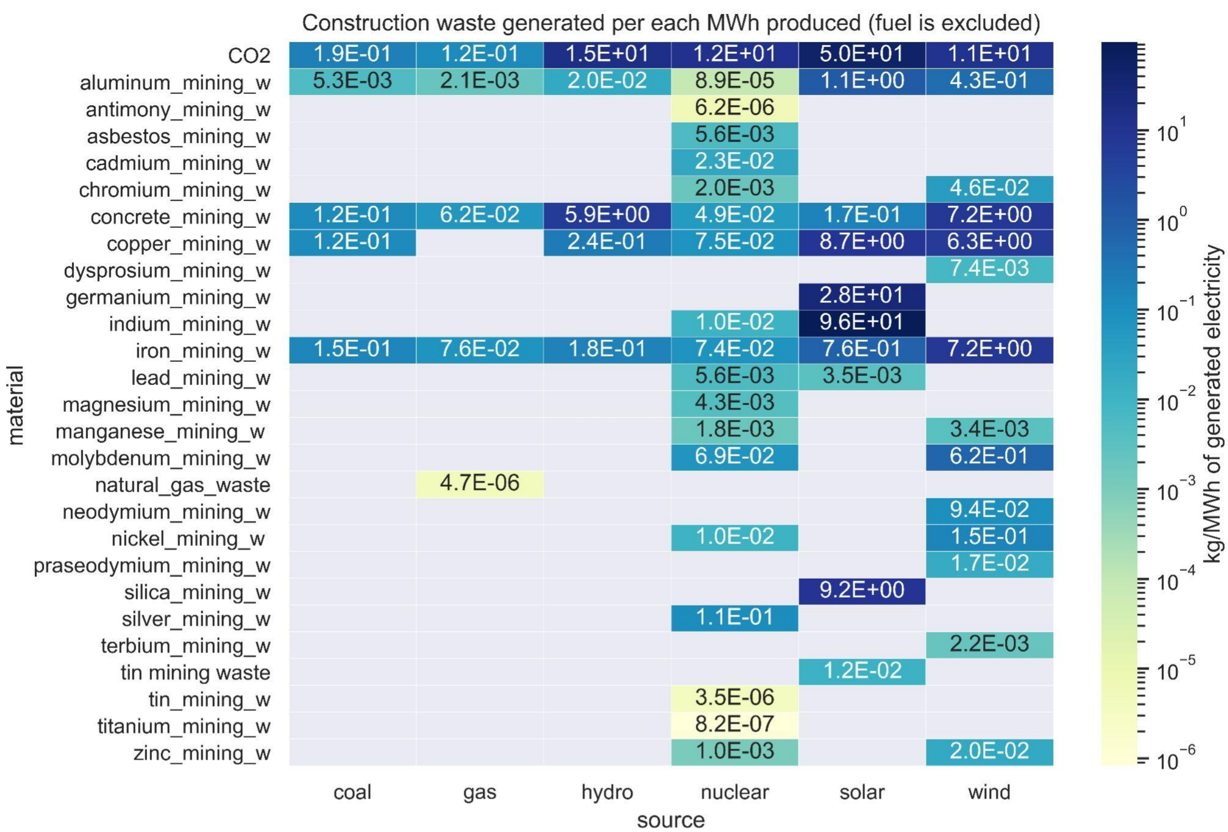

Figure 3. Raw material supply change.

Figure 4 shows the materials that may require substitution because of their scarcity and accelerated demand ("The Raw-Materials Challenge: How the Metals and Mining Sector Will Be at the Core of Enabling the Energy Transition" 2022). For example, Li and Te will see 700% and 800% increases by 2030 compared to 2010–2020 supply levels to satisfy the increasing demand.

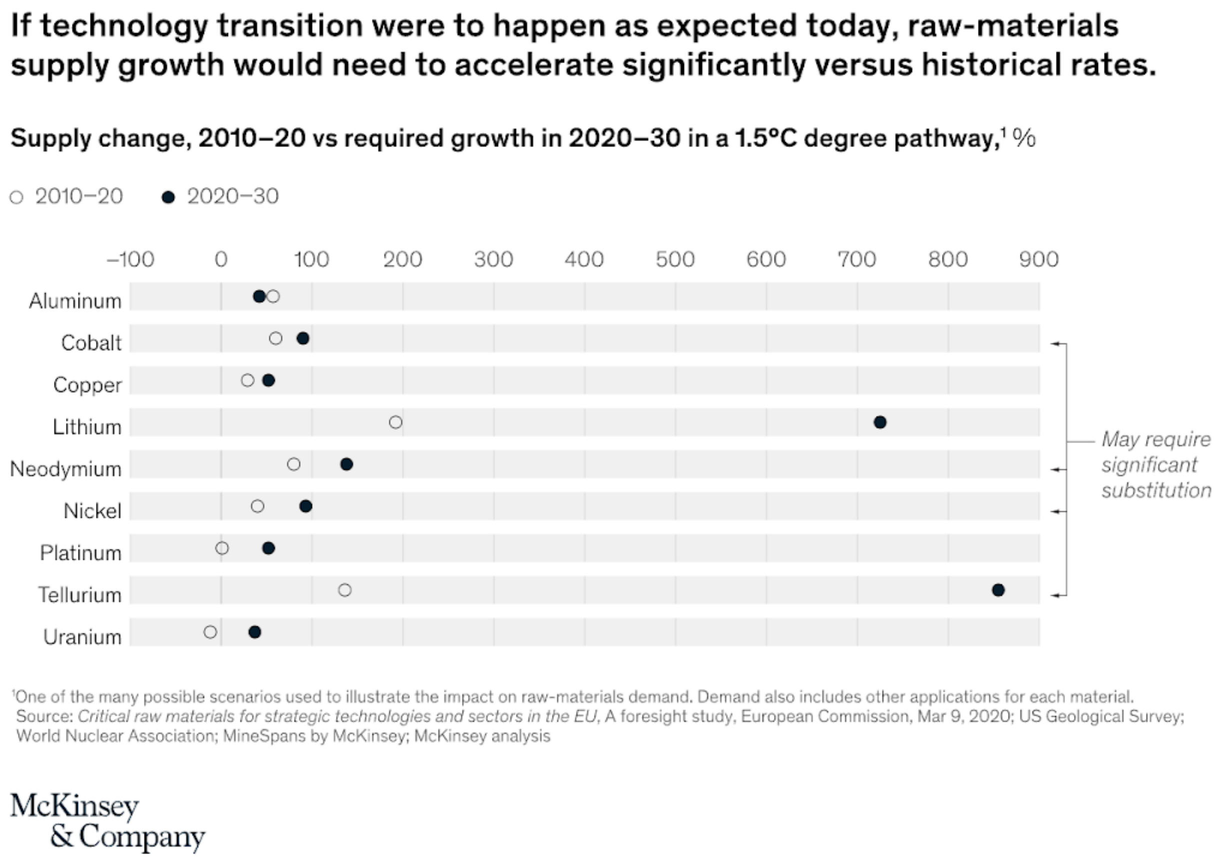

Figure 4. Raw material supply change.

3 SOLUTION FOR SUPPLY CHAIN AND ABANDONED MINES

3.1 ECONOMIC MOTIVATION

The United States has approximately 500,000 abandoned hard rock mines, and these mines have an estimated cleanup cost of up to $54 billion (Figure 5). However, hard rock mining firms are not required to make any payments to address this legacy cleanup cost ("The House Committee on Natural Resources" n.d.).

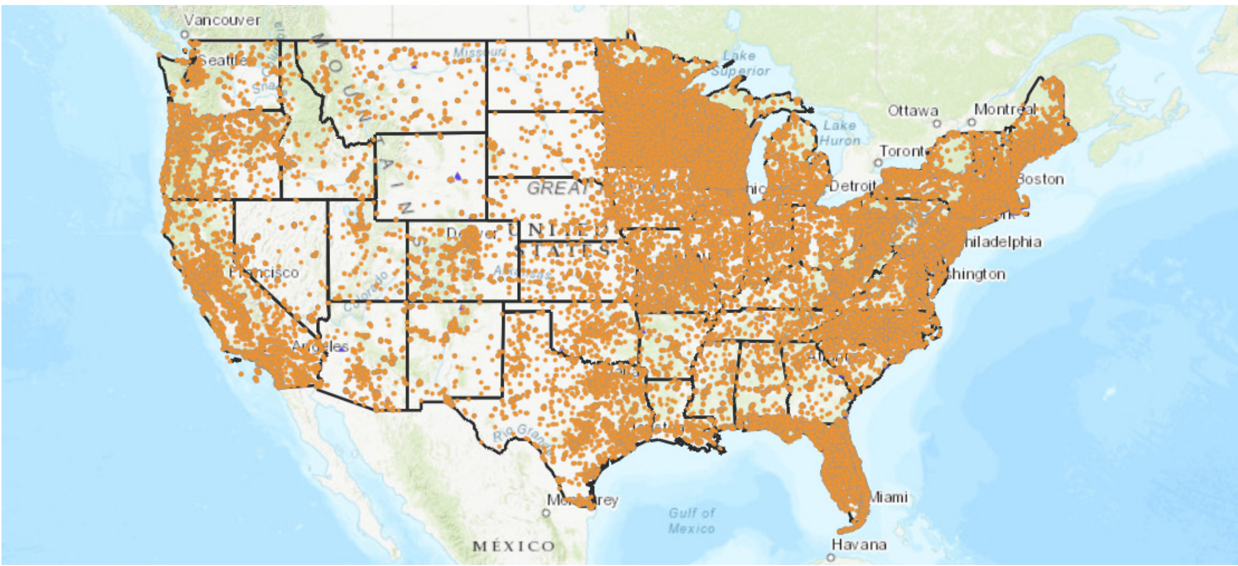

Figure 5. Map of abandoned US mines ("U.S. Environmental Protection Agency" 2001)**.**

Raw metal and mineral mining, finished production, and recycling must coexist to meet the rising demand for metals (Fu, Ueland, and Olivetti 2017; Gerst and Graedel 2008). The effects of the carbon added tax (CAT) on particular metals and their recycled counterparts are illustrated in Figure 6 (Cox et al. 2022). Many studies on material flow analysis focus on the Cu and steel recycling industries (Fu, Ueland, and Olivetti 2017; Glöser, Soulier, and Tercero Espinoza 2013; Ekman Nilsson et al. 2017); however, CAT economically affects the mining and production of raw metals more than twice as much as it affects recycled metal. Additionally, low-grade scrap metal losses are a significant problem for recycled metals. The municipal waste management system must be changed globally to address this problem, and a CAT may not supply enough money to support that change. The current supply of metals and minerals, even with a theoretical 100% recycling rate, would not be enough to satisfy present or future demand. For example, by 2050, the amount of above-ground Cu stocks needed per person is expected to increase 2–3.5 times. Material flow analyses show that because of the fundamental lack of above-ground stocks, current recycling rates can meet only a very small portion of this demand. Thus, supply-demand balances will increase the prices to meet the demand for these materials, making the abandoned ores a potentially lucrative venue for mining companies.

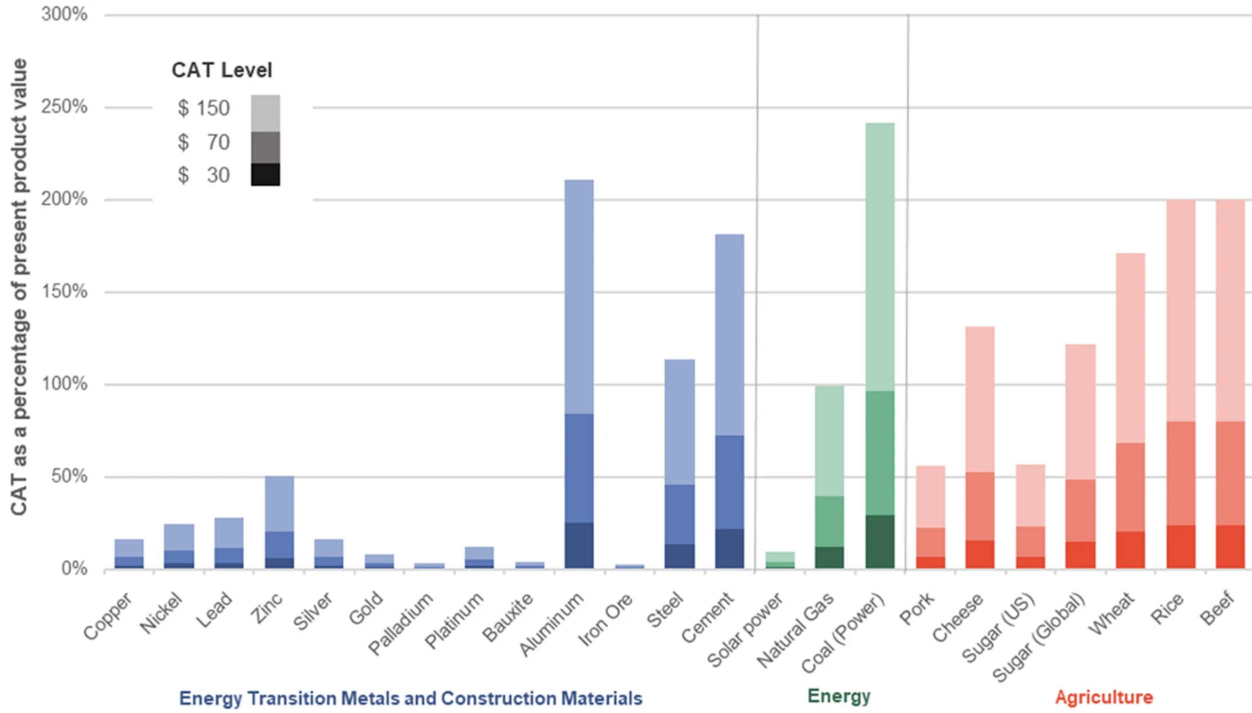

Figure 6. Three levels of CAT modeled as a percentage of present product value for selected commodities (Cox et al. 2022)**.**

The McKinsey report predicts a lack of materials, price increases, and the need for technological innovation and metal substitution as a result of the supply not responding quickly enough ("The Raw-Materials Challenge: How the Metals and Mining Sector Will Be at the Core of Enabling the Energy Transition" 2022). Although the demand for certain metals as raw materials will increase exponentially, the lead times for large-scale new greenfield assets can take up to 7 years and will necessitate a sizable capital investment before actual demand and price incentives are observed. Additionally, with increasingly complex and lower-quality deposits due to decreasing ore content of the mined deposits, miners will require significant monetary incentives (e.g., consistent Cu prices of more than $8,000–$10,000 per metric ton and Ni prices of more than $18,000 per metric ton) before large capital decisions are made. The industry will be unable to handle rapid exponential growth without slack in the system (e.g., strategic stockpiles and overcapacity). A combination of technological development on the supply side and widespread substitution and technological development on the demand side will occur—as was observed, for instance, with the past reduction of Co intensity in batteries.

3.2 FEASIBILITY

Taking into account the number of abandoned mines and their cleanup needs, the costs are enormous and are not covered by the mining companies. Thus, remining existing waste may help in offsetting these costs. The costs for the cleanup of abandoned mines are expected to be over $54 billion, and accounting for the aforementioned economic value, cleanup and recycling can be coupled with actions to reduce the amount of valuable materials lost, as well as incentivize mining companies to share the responsibility for cleanup activities and offset cleanup costs for taxpayers, provide job opportunities, and implement the circular economy strategy ("The House Committee on Natural Resources").

Because of the large amount of waste rock generated, coal mines present a viable option for remining and restoration initiatives. In partnership with the West Virginia Department of Environmental Protection, the University of West Virginia is exploring the extraction of rare earth materials from coal mining waste. This initiative will help with water cleanup and, as a side product, provide materials that are critical for green energy supply and alleviate the negative effects of initial mining activities (Skousen, Ziemkiewicz, and McDonald 2019). Using this method, acid mine drainage (AMD) from the northern and central Appalachian coal basins will be collected and treated to meet clean water standards. Then, the REEs, Al, and vital minerals such as Co and Mn will be extracted (Figures 7 and 8) (Ziemkiewicz n.d.). The carbon footprint of this process is about half that of a conventional mining and milling operation, according to a principal investigator ("U.S. Senate Committee on Energy and Natural Resources" n.d.).

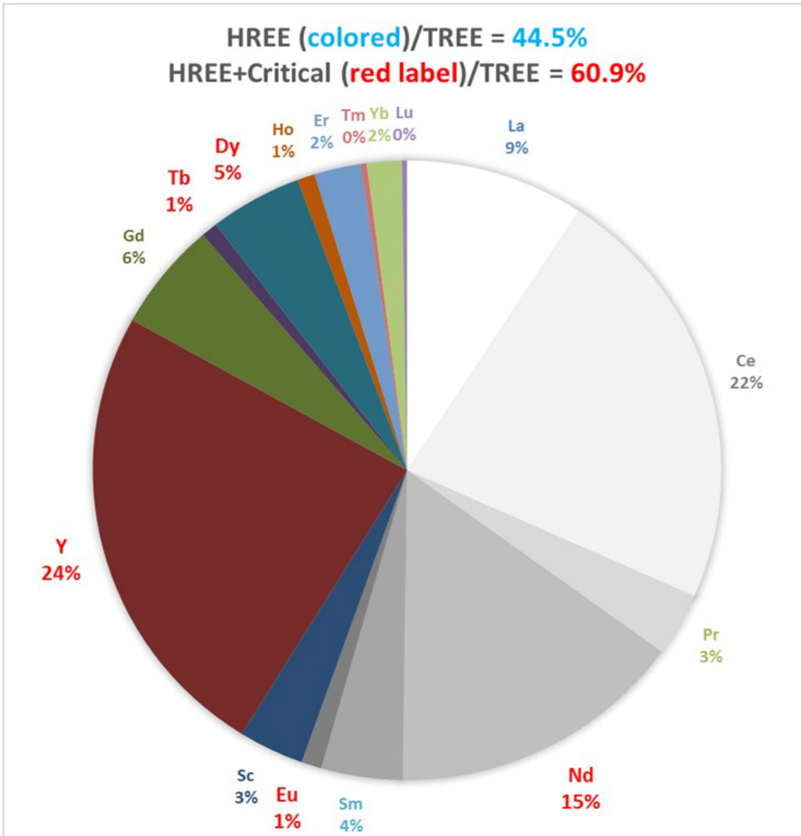

Figure 6. AMD contains a high proportion of the valuable and heavy REEs. Together, they comprise approximately 60% of the total REEs in Appalachian AMD.

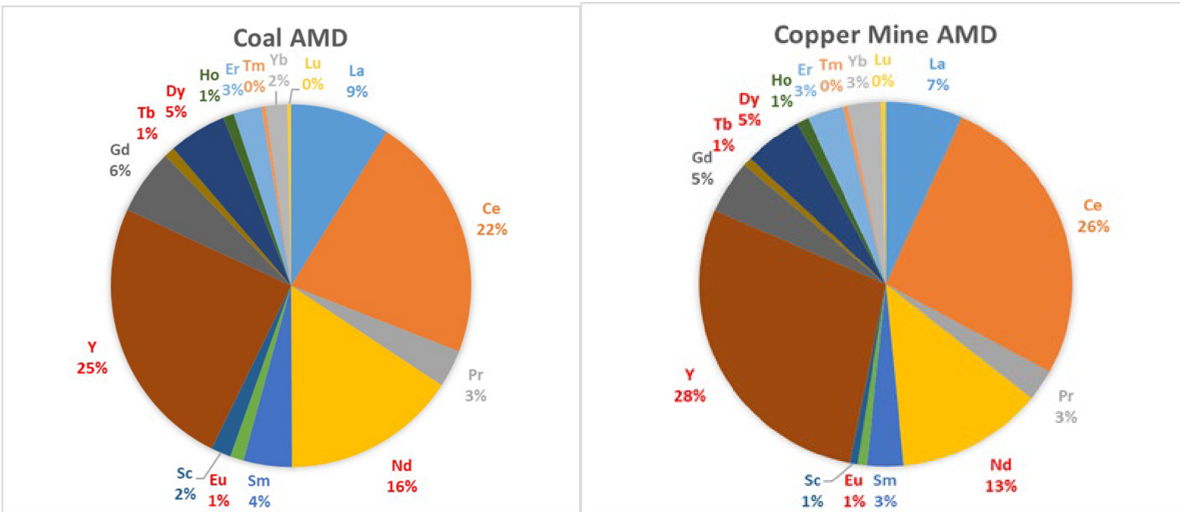

Figure 7. Distribution of REEs in coal and Cu mine AMD. The coal results represent 140 samples from northern and central Appalachian mines. The Cu AMD represents two samples from the Berkeley Pit in Butte, Montana. Red labels represent REEs ("U.S. Senate Committee on Energy and Natural Resources" n.d.)**.**

Companies that specialize in reprocessing mineral waste have volunteered their technical knowledge, including Magnetation (United States), which uses a magnetic separation technology; BioteQ (Canada), which combines sulfide precipitation and ion-exchange technologies ("Key Sectors" 2014); and Ecologix (United States), which uses physicochemical processes involving flocculation and sedimentation ("Mining Industry Wastewater Treatment Systems" 2018), (Lèbre, Corder, and Golev 2017).

At this stage, more research and funding for these technologies is required to provide a basis for an industrial-scale development, as well as opportunities to extract other elements.

3.3 ENVIRONMENTAL JUSTICE

Large open pits, chemical and mechanical processes, and other highly industrialized aspects of large-scale modern mining—along with a lack of economic support for the regions—can cause environmental justice (EJ) conflicts at various points in the extraction process. These occurrences generate an unequal distribution of negative effects on the environment and public health while companies benefit from the produced technologies without facing the negative effects of their production. The transition to clean energy should not further these injustices.

Mining has left a legacy of mining waste abandoned on 500,000 sites across the nation. Some are located on Native American lands or—as in the case of abandoned coal mines in central Appalachia—in marginalized communities who now suffer negative effects of these projects (Hendryx 2010). Finance company MSCI estimates that most of the US reserves for Co, Li, and Ni are located within 35 mi of Native American lands, and many groups associate mineral extraction with their historical memory of dispossession and the disruption of traditional lifestyles (Block n.d.; Keeling and Sandlos 2009).

Mining negatively affects populations in emerging countries such as South America, Africa, and Asia—from which the United States imports certain raw materials—by polluting local waters or depleting natural water reserves and increasing concerns over neocolonialism (Blair et al. 2022), (Bridge 2004). In the 1990s, a growing share of mineral exploration occurred in tropical regions around the world, including ecologically delicate or highly valuable conservation areas (Bridge 2004).

Communities may once again experience environmental issues related to mining as the demand for renewable energy materials increases and lower-quality deposits (i.e., those with toxic minerals present) are exploited. These activities will use more water and produce more waste rock to meet demands, adding to social and environmental issues (Giurco 2010). Mining is also an inherently invasive process, and mining eco-efficiency and technological approaches are limited, so adverse effects cannot be predicted fully. As the quality of deposits decreases, larger amounts of ore will be processed. Because of previous negative experiences with mining projects, local communities may oppose new mining operations before extraction begins and seek to protect land, water, or/and bioresources—especially when, despite frequent claims that mines infringe on rights to fish, hunt, and gather plants guaranteed by treaties, federal mining law gives private companies enormous power to stake claims and dig on public lands. These factors affect the livelihood of the area and agricultural opportunities. Thus, pristine mines have the potential to exacerbate social inequality and environmental injustice instead of mitigating existing problems related to abandoned sites that are inhabitable.

The approach would allow for extraction, quality control, and cleanup activities to some extent, depending on special treatment plans, the use of specialized equipment, and the nature of the waste. The approach would also provide jobs to the local communities, improve economic development, and extract valuable unused resources from the mining waste that is polluting rivers and groundwater. In this case, the local communities could be involved in the entire development, protecting their interests and environment that could otherwise be adversely affected.

4 CONCLUSION

As the transition to renewable energy sources receives more support, energy generated from renewable energy sources is expected to increase significantly by 2050 and lead to rapid demand for technology-specific materials. Energy security concerns have resulted in considering local raw materials extraction to avoid dependence on imports, and this may lead to intensifying mining activities and conflicts with local communities and tribes where ores are located.

This study explored remining abandoned mine waste to extract minerals and metals for technologies and REEs from economic, feasibility, and EJ perspectives. Remining may help reduce cleanup costs and prevent the mining of pristine lands, avoiding EJ issues. It could also provide an avenue for local communities to control cleanup efforts and provide jobs and materials to the manufacturers, while also generating a revenue with growing raw material prices. For the mining companies, it is a financial as well as risk to face an opposition from local communities to start an exploration of a new site and options for remining can be more welcomed if followed by cleanup activities. Hence increasing raw material prices due to increasing demand as well as the initiatives for localized production can be economic stimuli to help mining companies invest into remining option.

5 ACKNOWLEDGMENTS

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6 REFERENCES

Agency, International Renewable Energy. 2019. "Future of Solar Photovoltaic: Deployment, Investment, Technology, Grid Integration and Socio-Economic Aspects." *A Global Energy Transformation*.

Alsaleh, Ali, and Melanie Sattler. 2019. "Comprehensive Life Cycle Assessment of Large Wind Turbines in the US." *Clean Technologies and Environmental Policy* 21 (4): 887–903. https://doi.org/10.1007/s10098-019-01678-0.

Apergis, Nicholas, and James E. Payne. 2012. "Renewable and Non-Renewable Energy Consumption- Growth Nexus: Evidence from a Panel Error Correction Model." *Energy Economics* 34 (3): 733–38. https://doi.org/10.1016/j.eneco.2011.04.007.

Ballinger, Benjamin, Martin Stringer, Diego R. Schmeda-Lopez, Benjamin Kefford, Brett Parkinson, Chris Greig, and Simon Smart. 2019. "The Vulnerability of Electric Vehicle Deployment to Critical Mineral Supply." *Applied Energy* 255 (December): 113844. https://doi.org/10.1016/j.apenergy.2019.113844.

Barry, B. T. K. 2017. "Tin Processing." In *Encyclopedia Britannica*. https://www.britannica.com/technology/tin-processing.

Bauer, C., K. Treyer, T. Heck, and S. Hirschberg. 2015. "Greenhouse Gas Emissions from Energy Systems, Comparison, and Overview." *Reference Module in Earth Systems and Environmental Sciences*. https://doi.org/10.1016/b978-0-12-409548-9.09276-9.

Blair, James J. A., Ramón M. Balcázar, Javiera Barandiarán, and Amanda Maxwell. 2022. "Exhausted: How We Can Stop Lithium Mining from Depleting Water Resources, Draining Wetlands, and Harming Communities in South America." unknown. http://dx.doi.org/.

Block, Samuel. n.d. "Mining Energy-Transition Metals: National Aims, Local Conflicts." Accessed August 10, 2022. https://www.msci.com/www/blog-posts/mining-energy-transition-metals/02531033947.

Bridge, Gavin. 2004. "Mapping the Bonanza: Geographies of Mining Investment in an Era of Neoliberal Reform." *The Professional Geographer: The Journal of the Association of American Geographers* 56 (3): 406–21. https://doi.org/10.1111/j.0033-0124.2004.05603009.x.

"Clean Energy Demand for Critical Minerals Set to Soar as the World Pursues Net Zero Goals." IEA. Accessed August 9, 2022. https://www.iea.org/news/clean-energy-demand-for-critical-minerals- set-to-soar-as-the-world-pursues-net-zero-goals.

Cox, Benjamin, Sally Innis, Nadja C. Kunz, and John Steen. 2022. "The Mining Industry as a Net Beneficiary of a Global Tax on Carbon Emissions." *Communications Earth & Environment* 3 (1): 1–8. https://doi.org/10.1038/s43247-022-00346-4.

Dias, Patricia Alves, Silvia Bobba, Samuel Carrara, and Beatrice Plazzotta. 2021. "THE ROLE OF RARE EARTH ELEMENTS IN WIND ENERGY AND ELECTRIC MOBILITY An Analysis of Future Supply/demand Balances." unknown. https://doi.org/10.2760/303258.

DoE, U. S. 2015. "Quadrennial Technology Review 2015." *US Department of Energy, Washington, DC*.

Downing, James H. 2013. “Manganese Processing.” In *Encyclopedia Britannica*. https://www.britannica.com/technology/manganese-processing.

Downing, James H., and Frederick E. Bacon. 2013. “Chromium Processing.” In *Encyclopedia Britannica*. https://www.britannica.com/technology/chromium-processing.

Dunn, Jennifer B., Christine James, Linda Gaines, Kevin Gallagher, Qiang Dai, and Jarod C. Kelly. 2015. “Material and Energy Flows in the Production of Cathode and Anode Materials for Lithium Ion Batteries.” ANL/ESD-14/10 Rev. Argonne National Lab. (ANL), Argonne, IL (United States). https://doi.org/10.2172/1224963.

Eckermann, Dayne. 2021. “Materials Use in a Clean Energy Future.” Bright New World. June 26, 2021. https://www.brightnewworld.org/media/2021/1/27/materials-use-project.

Ekman Nilsson, Anna, Marta Macias Aragonés, Fatima Arroyo Torralvo, Vincent Dunon, Hanna Angel, Konstantinos Komnitsas, and Karin Willquist. 2017. “A Review of the Carbon Footprint of Cu and Zn Production from Primary and Secondary Sources.” *Minerals (Basel, Switzerland)* 7 (9): 168. https://doi.org/10.3390/min7090168.

Elchalakani, Mohamed, Tarek Aly, and Emad Abu-Aisheh. 2014. “Sustainable Concrete with High Volume GGBFS to Build Masdar City in the UAE.” *Case Studies in Construction Materials* 1 (January): 10–24. https://doi.org/10.1016/j.cscm.2013.11.001.

Fraunhofer, I. S. E. 2017. “Recent Facts about Photovoltaics in Germany.” *Fraunhofer Institute for Solar Energy Systems ISE, Freiburg*.

Fu, Xinkai, Stian M. Ueland, and Elsa Olivetti. 2017. “Econometric Modeling of Recycled Copper Supply.” *Resources, Conservation and Recycling* 122 (July): 219–26. https://doi.org/10.1016/j.resconrec.2017.02.012.

Gerst, Michael D., and T. E. Graedel. 2008. “In-Use Stocks of Metals: Status and Implications.” *Environmental Science & Technology* 42 (19): 7038–45. https://doi.org/10.1021/es800420p.

Giurco, Damien. 2010. *Peak Minerals in Australia: A Review of Changing Impacts and Benefits*. Institute for Sustainable Futures(University of Technology, Sydney; Department of Civil Engineering(Monash University). https://play.google.com/store/books/details?id=B80DtwAACAAJ.

Giurco, Damien, Elsa Dominish, Nick Florin, Takuma Watari, and Benjamin McLellan. 2019. “Requirements for Minerals and Metals for 100% Renewable Scenarios.” In *Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5°C and +2°C*, edited by Sven Teske, 437–57. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-05843-2_11.

Glöser, Simon, Marcel Soulier, and Luis A. Tercero Espinoza. 2013. “Dynamic Analysis of Global Copper Flows. Global Stocks, Postconsumer Material Flows, Recycling Indicators, and Uncertainty Evaluation.” *Environmental Science & Technology* 47 (12): 6564–72. https://doi.org/10.1021/es400069b.

Grandell, Leena, and Mikael Höök. 2015. “Assessing Rare Metal Availability Challenges for Solar Energy Technologies.” *Sustainability: Science Practice and Policy* 7 (9): 11818–37. https://doi.org/10.3390/su70911818.

Gschneidner, Karl A., Jr., and Vitalij K. Pecharsky. 2019. “Rare-Earth Element.” In *Encyclopedia*

Britannica. https://www.britannica.com/science/rare-earth-element.

Healy, Jack, and Mike Baker. 2021. "As Miners Chase Clean-Energy Minerals, Tribes Fear a Repeat of the Past." *The New York Times*, December 27, 2021. https://www.nytimes.com/2021/12/27/us/mining-clean-energy-antimony-tribes.html.

Hendryx, Michael. 2010. "Poverty and Mortality Disparities in Central Appalachia: Mountaintop Mining and Environmental Justice." *Journal of Health Disparities Research and Practice* 4 (3): 6. https://digitalscholarship.unlv.edu/jhdrp/vol4/iss3/6/.

"The House Committee on Natural Resources." Accessed August 10, 2022. https://naturalresources.house.gov.

Huber, Sophie Theresia, and Karl W. Steininger. 2022. "Critical Sustainability Issues in the Production of Wind and Solar Electricity Generation as Well as Storage Facilities and Possible Solutions." *Journal of Cleaner Production* 339 (March): 130720. https://doi.org/10.1016/j.jclepro.2022.130720.

Iea, Iea. 2020. "World Energy Balances: Overview." In . IEA Paris.

"International Aluminium Institute Publishes Global Recycling Data." Aluminium International Today. Accessed May 22, 2022. https://aluminiumtoday.com/news/international-aluminium-institute-publishes-global-recycling-data.

International Atomic Energy Agency. 1996. *Comparison of Energy Sources in Terms of Their Full-Energy-Chain Emission Factors of Greenhouse Gases: Proceedings of an IAEA Advisory Group Meeting*. IAEA. https://play.google.com/store/books/details?id=YLy_uQEACAAJ.

International Energy Agency. 2021. *The Role of Critical Minerals in Clean Energy Transitions*. OECD Publishing. https://play.google.com/store/books/details?id=YU4RzwEACAAJ.

"International Mine Water Association." 2002. *Mine Water and the Environment* 21 (3): 152–152. https://doi.org/10.1007/s102300200036.

Keeling, Arn, and John Sandlos. 2009. "Environmental Justice Goes Underground? Historical Notes from Canada's Northern Mining Frontier." *Environmental Justice* 2 (3): 117–25. https://doi.org/10.1089/env.2009.0009.

"Key Sectors." 2014. BQE Water. November 13, 2014. https://www.bqewater.com/key-sectors/.

Lèbre, Éléonore, Glen D. Corder, and Artem Golev. 2017. "Sustainable Practices in the Management of Mining Waste: A Focus on the Mineral Resource." *Minerals Engineering* 107 (June): 34–42. https://doi.org/10.1016/j.mineng.2016.12.004.

Lèbre, Éléonore, Martin Stringer, Kamila Svobodova, John R. Owen, Deanna Kemp, Claire Côte, Andrea Arratia-Solar, and Rick K. Valenta. 2020. "The Social and Environmental Complexities of Extracting Energy Transition Metals." *Nature Communications* 11 (1): 4823. https://doi.org/10.1038/s41467-020-18661-9.

Mason, J. E., V. M. Fthenakis, T. Hansen, and H. C. Kim. 2006. "Energy Payback and Life-Cycle CO2 Emissions of the BOS in an Optimized 3·5 MW PV Installation." *Progress in Photovoltaics: Research and Applications* 14 (2): 179–90. https://doi.org/10.1002/pip.652.

Matasci, Sara. 2021. "Solar Panel Size and Weight: How Big Are Solar Panels?" EnergySage Blog.

EnergySage. December 1, 2021. https://news.energysage.com/average-solar-panel-size-weight/.

"Mining Industry Wastewater Treatment Systems »." 2018. Ecologix Systems. September 27, 2018. http://www.ecologixsystems.com/industry-mining/.

Moore, Post, and Mysak. n.d. "Photovoltaic Power Plant Experience at Tucson Electric Power." *Atlantis Studies in Mathematics for Engineering and Science*. https://asmedigitalcollection.asme.org/IMECE/proceedings-abstract/IMECE2005/387/310293.

Moss, Tzimas, Kara, Willis, and Arendorf. "Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies." *European Commission*.

Muwanguzi, Abraham J. B., Andrey V. Karasev, Joseph K. Byaruhanga, and Pär G. Jönsson. 2012. "Characterization of Chemical Composition and Microstructure of Natural Iron Ore from Muko Deposits." *International Scholarly Research Notices* 2012. https://downloads.hindawi.com/archive/2012/174803.pdf.

Navarro, M. C., C. Pérez-Sirvent, M. J. Martínez-Sánchez, J. Vidal, P. J. Tovar, and J. Bech. 2008. "Abandoned Mine Sites as a Source of Contamination by Heavy Metals: A Case Study in a Semi-Arid Zone." *Journal of Geochemical Exploration* 96 (2): 183–93. https://doi.org/10.1016/j.gexplo.2007.04.011.

Pacca, Sergio, and Arpad Horvath. 2002. "Greenhouse Gas Emissions from Building and Operating Electric Power Plants in the Upper Colorado River Basin." *Environmental Science & Technology* 36 (14): 3194–3200. https://doi.org/10.1021/es0155884.

Ponikvar, Adolph L., and Frank E. Goodwin. 2013. "Lead Processing." In *Encyclopedia Britannica*. https://www.britannica.com/technology/lead-processing.

"President Biden's Bipartisan Infrastructure Law." 2021. The White House. November 6, 2021. https://www.whitehouse.gov/bipartisan-infrastructure-law/.

"Rare Earth Elements Project Receives Federal Funding." Accessed August 1, 2022. https://www.uwyo.edu/uw/news/2020/06/rare-earth-elements-project-receives-federal-funding.html.

"Renewable Electricity Growth Is Accelerating Faster than Ever Worldwide, Supporting the Emergence of the New Global Energy Economy." IEA. Accessed May 31, 2022. https://www.iea.org/news/renewable-electricity-growth-is-accelerating-faster-than-ever-worldwide-supporting-the-emergence-of-the-new-global-energy-economy.

Richards, Alan W. 2019. "Zinc Processing." In *Encyclopedia Britannica*. https://www.britannica.com/technology/zinc-processing.

Samuel Carrara, Patricia Alves Dias, Beatrice Plazzotta, Claudiu Pavel. 2020. "Raw Materials Demand for Wind and Solar PV Technologies in the Transition towards a Decarbonised Energy System." Publication Office of the European Union, Luxembourg.

Schwarz, H-G. 2004. "Aluminum Production and Energy." *Encyclopedia of Energy*. https://doi.org/10.1016/b0-12-176480-x/00372-7.

Sim, Min-Sub, Hyeon-Tae Ju, Kwan-Soo Kim, and Ji-Soo Kim. 2014. "Case Studies of Geophysical Mapping of Hazard and Contaminated Zones in Abandoned Mine Lands." *The Journal of Engineering Geology* 24 (4): 525–34. https://doi.org/10.9720/kseg.2014.4.525.

Skousen, Jeffrey G., Paul F. Ziemkiewicz, and Louis M. McDonald. 2019. "Acid Mine Drainage Formation, Control and Treatment: Approaches and Strategies." *The Extractive Industries and Society* 6 (1): 241–49. https://doi.org/10.1016/j.exis.2018.09.008.

Soares, Aline. 2022. "Copper Scrap Boasts Decarbonization Benefits amid Challenging Market Dynamics." March 3, 2022. https://www.spglobal.com/marketintelligence/en/news-insights/research/copper-scrap-boasts-decarbonization-benefits-amid-challenging-market-dynamics.

Sonter, Laura J., Marie C. Dade, James E. M. Watson, and Rick K. Valenta. 2020. "Renewable Energy Production Will Exacerbate Mining Threats to Biodiversity." *Nature Communications* 11 (1): 4174. https://doi.org/10.1038/s41467-020-17928-5.

Sutulov, Alexander, and Chun Tsin Wang. 2018. "Molybdenum Processing." In *Encyclopedia Britannica*. https://www.britannica.com/technology/molybdenum-processing.

"The Raw-Materials Challenge: How the Metals and Mining Sector Will Be at the Core of Enabling the Energy Transition." 2022. McKinsey & Company. January 10, 2022. https://www.mckinsey.com/industries/metals-and-mining/our-insights/the-raw-materials-challenge-how-the-metals-and-mining-sector-will-be-at-the-core-of-enabling-the-energy-transition.

United Nations Economic Commission For Europe. 2022. "Carbon Neutrality in the UNECE Region: Integrated Life-Cycle Assessment of Electricity Sources." UNECE.

"U.S. Environmental Protection Agency." 2001. *Choice* 38 (12): 38Sup – 245–38Sup – 245. https://doi.org/10.5860/choice.38sup-245.

U. s. Government Printing Office. 2011. *Minerals Yearbook: Metals and Minerals 2009*. U.S. Government Printing Office. https://play.google.com/store/books/details?id=IFInpwAACAAJ.

"U.S. Senate Committee on Energy and Natural Resources." n.d. Accessed August 10, 2022. https://www.energy.senate.gov/services/files/3FE0D2F4-1001-44FF-B0C1-9B535DA41935

Van Zalk, John, Behrens Paul. 2018. "The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S." *Energy Policy* 123. https://doi.org/10.1016/j.enpol.2018.08.023.

Verma, Shalini, Akshoy Ranjan Paul, and Nawshad Haque. 2022. "Assessment of Materials and Rare Earth Metals Demand for Sustainable Wind Energy Growth in India." *Minerals* 12 (5): 647. https://doi.org/10.3390/min12050647.

Wilburn, David R. 2011. "Wind Energy in the United States and Materials Required for the Land-Based Wind Turbine Industry from 2010 through 2030." *Scientific Investigations Report*. US Geological Survey. https://doi.org/10.3133/sir20115036.

Wise, Edmund Merriman, and John Campbell Taylor. 2013. "Nickel Processing." In *Encyclopedia Britannica*. https://www.britannica.com/technology/nickel-processing.

Zhang, Tong, Xunpeng Shi, Dayong Zhang, and Junji Xiao. 2019. "Socio-Economic Development and Electricity Access in Developing Economies: A Long-Run Model Averaging Approach." *Energy Policy* 132 (September): 223–31. https://doi.org/10.1016/j.enpol.2019.05.031.

Ziemkiewicz, Paul. n.d. "WVU Awarded $5 Million to Continue Rare Earth Project, Build Acid Mine Drainage Treatment Facility." Accessed August 10, 2022. https://wvutoday.wvu.edu/stories/2019/10/01/wvu-awarded-5-million-to-continue-rare-earth-project-

build-acid-mine-drainage-treatment-facility.