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Unlocking Rare Earth Elements from Coal Waste: Pennsylvania's Opportunity

MAY 2026

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Kleinman Center
for Energy Policy

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Rare Earth Elements: Strategic Importance

Rare earth elements (REEs), vital to clean energy technologies and national security, are at the center of a growing geopolitical crisis. Traditional sourcing pathways face escalating constraints and vulnerabilities, particularly due to China's dominance over supply chains, highlighting the urgent need for secure domestic alternatives (Serpell et al. 2021; Kirshner 2025; Holley et al. 2025).

While many studies emphasize resource constraints within the United States, the approach outlined here—extracting REEs from abundant coal ash—directly addresses and fills these critical gaps. Pennsylvania, home to extensive coal ash repositories, can uniquely leverage this industrial waste, turning environmental liabilities into strategic economic assets. **While policy priorities and market conditions continue to evolve, the strategic importance of securing domestic REE supply remains consistent.**

Current Supply Risks

REEs are a group of 17 chemically similar elements (Figure 1) that are critical for manufacturing many high-tech products. In particular, REEs are used to make powerful and efficient permanent magnets, which have become indispensable to a growing list of consumer and industrial products (Tradium GmbH, n.d.). These have been used for decades in green technologies like wind turbines and electric vehicles, making REEs critical ingredients for the transition to a low-carbon future.

More recently, they have also become indispensable to national security infrastructure, such as missile guidance systems, satellites, and the processors and components that drive artificial intelligence. As an example, a single F-35 fighter jet contains about 920 pounds of REE materials (Bailey Grasso 2013).

As global demand for these technologies accelerates, securing reliable and sustainable REE supply has become a strategic priority for economic resilience and geopolitical leverage, as well as—as decarbonization priorities evolve across administrations—achieving climate goals. **We recommend protecting and expediting federal funding, ensuring timely allocation of previously authorized IRA and IIJA funding for REE recovery projects (Rep. DeFazio 2021; Rep. Yarmuth 2022).**

Figure 1: Rare Earth Elements

LIGHT RARE EARTH ELEMENTS (LREEs)								HEAVY RARE EARTH ELEMENTS (HREEs)								
21	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	33
Sc	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y
Scandium 22 ppm	Lanthanum 39 ppm	Cerium 66.5 ppm	Praseodymium 9.2 ppm	Neodymium 41.5 ppm	Promethium <<0.001 ppm	Samarium 7.05 ppm	Europium 2 ppm	Gadolinium 6.2 ppm	Terbium 1.2 ppm	Dysprosium 5.2 ppm	Holmium 1.3 ppm	Erbium 3.5 ppm	Thulium 0.52 ppm	Ytterbium 3.2 ppm	Lutetium 0.8 ppm	Yttrium 33 ppm

LANTHANIDES

List of the 17 rare earth elements with their atomic number, abbreviation, full name, and their abundance in the Earth's crust in parts per million (ppm).

Recent supply chain disruptions are the result of both increasing demand straining global production capacity, and production and processing consolidation in China. Global demand is expected to triple by 2040 (Detry et al. 2023), and at least 20 new conventional mining projects will need to be launched to avoid shortfalls. As a result, the Department of Energy identifies several REEs as "critical", anticipating supply risk as early as this year (NETL, n.d.).

The U.S. has only one operational REE mine—Mountain Pass, CA, producing 16% of global supply—and one newly permitted mine—Ramaco's Brook Mine in WY, announced as of July 2025—but no capacity for processing. Mined material is sent to China to refine ores into pure REEs.

China has large natural reserves of REEs, estimated at twenty times the amount in the U.S. (Cordier 2025), and also benefits from decades of infrastructure investment. In the global marketplace, China currently accounts for 63% of REE mining and 85% of processing. Such a monopoly adds to global supply chain vulnerability concerns, highlighted by China's suspension of REE exports to the U.S. in May 2025, in retaliation for U.S. tariff increases.

For a reliable domestic REE supply, the U.S. is starting at square one with little production capacity and zero processing capacity. Developing a new mine in the U.S. takes an average of 29 years (Bonakdarpour et al. 2024). Furthermore, processing REE ore results in large volumes of hazardous waste, causing environmental concerns and potential regulatory delays.

The world's largest REE mine, located in China, is plagued by severe air and water pollution from heavy metals, leaching acid, and radioactive byproducts. Managing such potential impacts in the U.S. is already proving to be a bottleneck for buildout of domestic facilities (Hoyle 2025). The Department of Defense has set a goal to develop a "mine-to-magnet" domestic supply chain for defense-related needs, and has spent hundreds of millions in the past few years to fund both mining and processing facilities (Lopez 2024; Baskaran and Schwartz 2025).

Recent policy signals suggest potential efforts to expedite permitting timelines for these projects, potentially at the expense of environmental and social impacts (Robbins 2026). However, building a REE industry from scratch, especially one that is capable of fully satisfying domestic needs, will still likely take decades.

We recommend explicitly including REE recovery from secondary source in permitting regulations, reducing uncertainty and promoting rapid infrastructure deployment, while ensuring the protection of communities and the environment by implementing community benefit agreements (DOE 2024).

Conventional and Innovative Sources of REEs

REEs are rarely found in concentrated and economically extractable forms, making their recovery challenging and costly (McNulty et al. 2022). Due to their physical characteristics (large ionic radius, high ionic charge, high atomic weight), REEs don't fit into the crystal lattice of most minerals and tend to accumulate into specific mineral phases through natural or industrial processes (Balaram 2019).

In nature, the concentration of REEs in certain rocks and minerals is related to magmatic processes (e.g., fractional crystallization) and processes involving water-rock interactions (e.g., diagenesis, weathering, hydrothermal activity). The primary sources of REEs are carbonatites, a rare type of igneous rock primarily composed of carbonate minerals, including calcite and dolomite, and placers, dense sediments in river beds or lake sediments downstream of REE-bearing rocks (Balaram 2023), like in the Yellow River or the Rhine (Klein et al. 2022). REEs are also found in ion adsorption clays (e.g., kaolinite) (McNulty et al. 2022).

Geological processes that concentrate REEs in rocks and minerals are slow and can take millions of years to accumulate REEs enough to be economically recoverable. However, industrial processes involving the combustion of mineral feedstocks like coal and iron ore produce ashes and slags that tend to concentrate REEs, increasing the economic recoverability of REEs (Stojkovic et al. 2024; Senior et al. 2020).

As demand grows, more diverse sources of REEs are investigated for mining exploration, including deep sea resources like ferromanganese nodules, seamount crusts, and sedimentary phosphates. Countries like the U.S., China, India, Japan, and Russia, along with private companies, are exploring the feasibility of lunar mining, maybe by the end of the decade (Xu 2020; Elvis et al. 2020).

The extraction of REEs from the deep ocean and the Moon can create governance issues as these are international territories. Mining in the deep ocean can also disturb the fragile ecosystems and result in environmental disasters. Sourcing REEs from industrial wastes in the United States, including coal ash, could be a way to avoid governance issues and lower environmental risks of mining and metal processing through stronger work and environmental regulations. In recent year, startups begun investigating REE recovery from industrial waste streams (Elliott 2025; Radin 2025; Businesswire 2025).

Because of the unique characteristics of REEs, some industrial processes concentrate REE in their waste streams. These waste streams are produced in large quantities by the mining industry (e.g., acid mine drainage (AMD), red mud, gem mining waste, coal waste piles, and abandoned mine lands) and heavy industries (e.g., coal ashes, phosphogypsum, slags, dusts). Early work by Goldschmidt (1935) observed that REEs concentrate in coal ash relative to the parent coal and the Earth's crust, but at the time, they were considered impurities and potential sources of pollution.

Despite climate goals, many countries still use coal for electricity generation and in industrial processes (Wu et al. 2022). China burns about 4 billion tons of coal annually, producing over 500 million tons of coal ash, and U.S. coal ash production has declined from a peak of ~130 million tons in 2014 to ~60–75 million tons annually in recent years (ACAA 2022), creating substantial domestic feedstock for REE extraction. However, extraction processes must also account for potential environmental risks, such as the release of radioactive elements like radium, thorium, and uranium found in coal ash (García et al. 2020, Thompson et al., 2018).

Although REE concentrations in coal ash (80–1200 ppm) are lower than in mined ores (800–1300 ppm) (Balaram 2019; DOE 2022), the economic value and environmental benefits may offset extraction costs. Recent technical assessments suggest that extracting high-purity REEs from coal ash could be economically viable and significantly faster to scale compared to traditional mining (DOE 2022; Granite et al. 2023; Hower et al. 2025). As detailed in recent research, domestic wastes such as coal ash hold sufficient REEs to meet national demand of 10,000 tons per year (Granite et al. 2023).

Pennsylvania, particularly burdened by coal-related environmental legacies, could leverage these benefits, creating high-quality jobs in extraction and metallurgical processing while mitigating pollution. In Pennsylvania alone, ash dumps contain more than 284 million cubic yards (217 million cubic meters) of coal ash, and all plants with available data but one are contaminating drinking water above federal safe drinking water standards, likely via unlined ponds (EarthJustice 2025).

Strengthening of EPA regulations (EPA 2014, 2025, 2024) requiring reporting of coal ash dumps, landfills, and ponds is providing more clarity on the amount of coal ash and the type of storage, and is setting deadlines for the closure of environmentally harmful sites.

Although REE concentrations in raw AMD are typically in the 0.001 parts per million (ppm) range, treatment processes like neutralization or lime precipitation can concentrate REEs into solid residues. For example, uranium mine effluent in Brazil contains 0.13 ppm REEs, and treated precipitates can contain up to 7% REE (Silva et al. 2022). In the U.S., treated AMD from coal basins showed REE concentrations ranging from 29 to 1286 ppm, and these treatment processes are already required by the Clean Water Act (Vass et al. 2019).

Recovery methods such as ion exchange, solvent extraction, and adsorption are being studied, especially when combined with the removal of toxic pollutants like arsenic and other heavy metals. AMD is particularly harmful to the environment and even if the operating mines need to regulate their output, abandoned mines can still spill AMD in streams and rivers. In Pennsylvania, AMD impairs over 5,500 miles of streams, including 1,800 stream miles of the state's portion of the Chesapeake Bay watershed (Blankenship 2025). As an example, West Virginia has been remediating the acidity of the streams while also recovering REEs (Rojanasakul 2025).

Recycling electronic waste has also gained attention as an alternative REE supply, with the benefit of lower environmental concerns and avoiding mining costs. E-waste items like magnets, nickel-metal hydride batteries, hard drives, loudspeakers and LEDs are now being explored as viable REE recovery sources (Dev et al. 2025). Over 50 million tons of electronic waste are generated globally each year, much of which contains REEs like Neodymium, Praseodymium, Dysprosium, and Terbium. These valuable elements can be recovered and reused, supporting sustainable development through a circular economy.

However, REE recycling remains limited—only about 2% of global supply is currently recovered due to challenges like low REE content in devices, complex usage patterns, and the lack of cost-effective extraction methods (Patil et al. 2022). Despite this, countries like the U.S. and Japan are investing in REE recycling research, especially from end-of-life products like Nd-Fe-B magnets, as a way to reduce dependence and address future supply risks. The REE recycling industry can learn from other critical mineral recycling processes, like those that recycle Li, Cu, Ni, and other metals from black mass, battery cathodes from lithium ion batteries (St. John 2023; Daly 2025; Skok 2025).

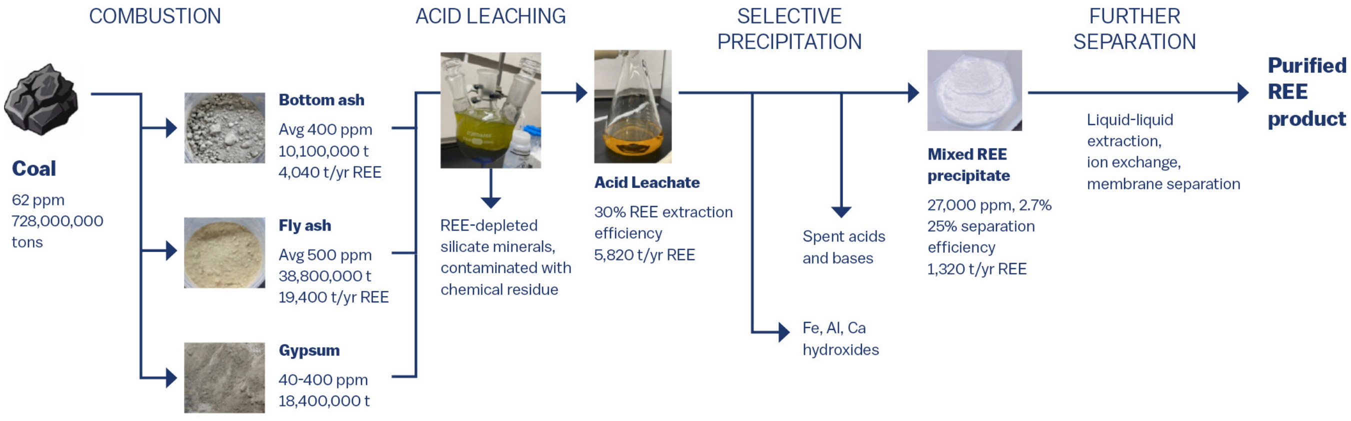
REE Extraction Potential from Coal Ash

Coal ash has between 80 and 1200 ppm REEs (average 400 ppm) and has been landfilled in the United States since the 1960s and the enactment of the Clean Air Act (Lattanzio 2022). Approximately 1.5 billion tons of coal combustion products have been landfilled since 1991 (DOE 2022). In 2022, the U.S. produced more than 75 million short tons of coal ash (and as much as 130 million tons in 2014) (ACAA 2022). Extraction from coal ash avoids hazards from traditional REE mining practices like open-pit mining and air pollution through smelting and water contamination during disposal (Long 2013).

Uncombusted coal has on the order of 100 ppm REEs, and the concentration is highly heterogeneous, with some parts of the coal seams having much higher (1500–1600 ppm) or lower levels (62–81 ppm) (DOE 2022; Finkelman 1993; Lin et al. 2017, 2018). For comparison, promising natural REE deposits have between 800–1300 ppm total REE concentration, comparable values to those in REE enriched coal ashes (Balaram 2019). Coal ashes vary in REE concentration and physical properties depending on the class of coal being combusted, and whether the ash is fresh or landfilled.

During combustion, REEs concentrate in the ash fraction as carbon is combusted and volatiles escape in the gas phase, and REE enrichment in the ash phases has been recorded in literature between 7 and 12-fold increase (Stojkovic et al. 2024; Senior et al. 2020). A common method for extracting REEs from coal ash is acid leaching (Figure 2). Strong acids concentrate REEs in solution, leaving REE-depleted silicates, contaminated with chemical residue.

Figure 2: REE Extraction From Coal Ash



The products of the combustion of coal are enriched in REEs, and acid leaching and selective precipitation steps help with REE enrichment.

For further use or disposal, this solid waste must be neutralized with a weak base solution as to not further contaminate groundwaters with acid residue. The recovery process is conceptually similar to the clean-closure method of closing coal ash impoundments (EarthJustice 2021). In traditional clean-closure, ash is removed entirely to a lined landfill or for beneficial reuse, rather than the cap-in-place method which threatens contaminant and heavy metal leakage into the groundwater.

Adding in a REE-extraction step removes many metal contaminants and could be performed between removal from unlined ash impoundments but before beneficial reuse or redisposal. Clean-closure results in job creation and economic activity in addition to its environmental benefits.

Prior to leaching, we can increase surface area and reactivity by treating coal ash with other reagents or employing mechanochemical or microwave treatment to enhance reactive surface area and extraction efficiency. Following leaching, standard separation and purification methods are applied to isolate REEs at high purity. REE value recovery depends on both the volume (throughput) and purity (selective separation) of the final product; higher purity REEs (99.9%+) fetch higher prices than mixed rare earth oxides.

Approximately 1.5 billion tons of coal combustion products have been landfilled from 1991 to 2016 and, presuming 100% recovery of an average concentration of 400 ppm, this stockpile could produce 661,000 tons of REEs (Figure 2) (Senior et al. 2020). In natural sources like coal and the earth's crust, REEs exist in fairly uniform relative concentration to each other: based on our data, about 33% of the total REEs are magnet REEs of value (Pr, Nd, Dy, Tb), with Nd making up the lion's share of 25%. Thus, the stockpiled landfilled coal ash could supply 218,000 tons of valuable magnet REEs. In perspective, the rate of consumption of REEs in 2023 was: 4,300 tons Nd, 4,400 tons, Dy, and 40 tons Pr per year (Granite et al. 2023).

Some hurdles facing REE extraction from secondary sources include operating costs of purification, and handling risks due to the concentration of radioactive metals like thorium and uranium often present in REE containing resources (García et al. 2020; Thompson et al. 2018).

Sourcing REEs from secondary sources is appealing compared to traditional REE mining from a cost-benefit perspective. Use of these resources may be quicker to create domestic supply because the mining steps have already been performed, and the process offers additional benefits in the form of coal waste remediation (DOE 2022; Granite et al. 2023; Hower et al. 2025). However, because of the low concentration of REE in the feedstock and the need to create a whole new industry, financial incentives are needed to bolster the industry and incentivize REE sourcing from secondary rather than primary sources.

Pennsylvania's Advantage

Pennsylvania is one of the nation's top coal ash-generating states. The state has a long standing history of energy production and steel making, associated with a robust transportation infrastructure and education programs in mining and metallurgy. These opportunities are shown on Figure 3, along with associated environmental hazards, and communities impacted by the energy transition.

Coal communities that have experienced economic disruption from the energy transition could particularly benefit -from REE extraction from coal ash and other secondary sources (e.g., steel slag, e-waste) if Pennsylvania can fully leverage its assets as a major energy exporting state, including its many railroads to transport materials.

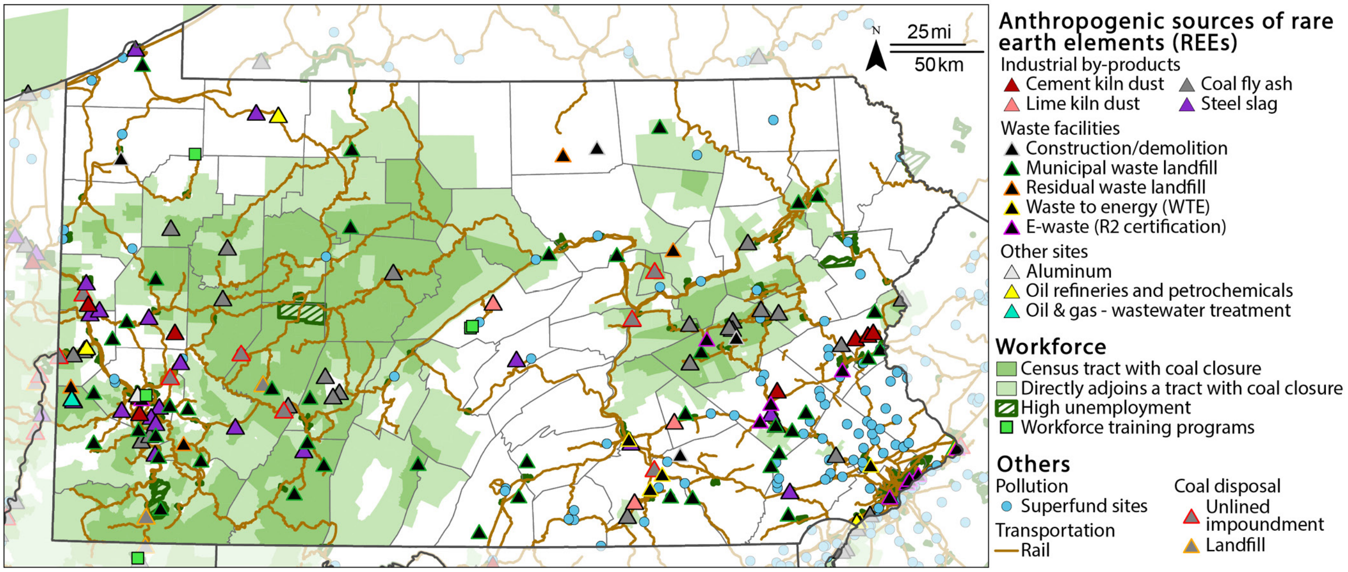
As highlighted in recent reporting, initiatives transforming coal waste into valuable materials for sustainable technologies show significant promise for revitalizing local economies. Such initiatives align closely with existing community expertise in metallurgical and industrial engineering, providing both environmental remediation and long-term economic renewal (Griswold 2022).

Universities like Penn State (PennState, n.d.-a), Carnegie Mellon (Carnegie Mellon University, n.d.), and Columbia University (Columbia University 2020) have training programs dedicated to mining and/or metallurgy. Part of their research is shifting toward REEs, with Penn State's Center for Critical Minerals (C2M) receiving a $4.99M DOE grant to build domestic supply chain for critical minerals (Craig 2024; Hess 2025), or Lehigh University Energy Research Center (ERC) receiving a $2.5 million grant from DOE to obtain REE from wastewater and waste streams (Lehigh University 2024).

Mining and metallurgy societies like the Pittsburgh's chapter of the Society for Mining, Metallurgy, and Exploration (SME, n.d.), the Penn State Mining Society (PennState, n.d.-b), the WVU Society for Mining, Metallurgy, and Exploration (West Virginia University, n.d.) can also play a critical role in strengthening the supply chain for REE extraction.

Skills required for REE extraction from secondary sources are similar to the ones needed in the mining, metallurgy, and waste management industries. We recommend leveraging local expertise to foster workforce development programs that capitalize on Pennsylvania's metallurgical and mineral heritage in the industrial, academic, and private sectors.

Figure 3: Potential Industrial Sources of Rees, Environmental Concerns, and Social Considerations



Source: Kirchofer et al. 2013; EPA 2023; The White House, n.d.; EarthJustice 2022; EPA, n.d.; SERI 2020.

Recovering REEs from legacy coal ash also presents an opportunity to address ongoing environmental contamination, especially in and around the Pittsburgh region and the Schuylkill County (Figure 3). REEs and other metals in coal ash can be mobilized under leaching conditions, which facilitates recovery but also contributes to environmental risk—a benefit for REE recovery, but a liability for legacy stockpiles. As a result, groundwater testing around coal ash impoundments often shows elevated levels of toxic elements (Chen et al. 2024).

Unfortunately, these impoundments have historically been poorly managed and 94% of regulated coal ash ponds are unlined (Figure 3), allowing leached material to enter groundwater. Federal laws regulating coal ash management are complicated, which inhibits enforcement by under-funded state regulators (Gaffney 2023). For example the New Castle Generating Station, near Pittsburgh, has serious heavy metal contamination in groundwater resulting from three million tons of impounded ash, but requirements for monitoring and remediation are unclear (The Environmental Integrity Project and Earthjustice 2022).

From a community benefits perspective, incentivizing REE extraction from sites like this would both remediate ongoing environmental pollution and create opportunities for new industries in regions historically shaped by the coal industry. For Pennsylvania, this presents a win-win opportunity to position the state as a leader in domestic critical mineral production while simultaneously resolving environmental liabilities.

Pennsylvania's current rule on beneficial reuse of coal ash mainly focuses on the construction and mining industries, and for use as soil substitutes or additives (PA 2010). Depending on the type of reuse, a set of restrictions, chemical analyses, and monitoring requirements aims to ensure the protection of water resources.

Other beneficial reuse also includes "The extraction or recovery of one or more materials and compounds contained within the coal ash" (PA 2010) under certain conditions, which could apply to REE extraction. As of today, the rule would allow for REE extraction from coal ash but could be amended to include a specific section on REE extraction to clarify the permitting process and state explicitly how radioactive waste associated with REE extraction should be handled.

We recommend providing financial incentives and legislative backing, similar to the RisePA program for decarbonization (PA 2026c), to support state-level pilot projects, starting with those demonstrating viable REE extraction from coal ash in Pennsylvania. To do so, the state could dedicate part of AML/AMD remediation fund for REE projects from secondary sources (PA 2026a). It could also extend the Coal Refuse Energy and Reclamation Tax Credit to favor facilities extracting REE from their coal ash (PA 2026b).

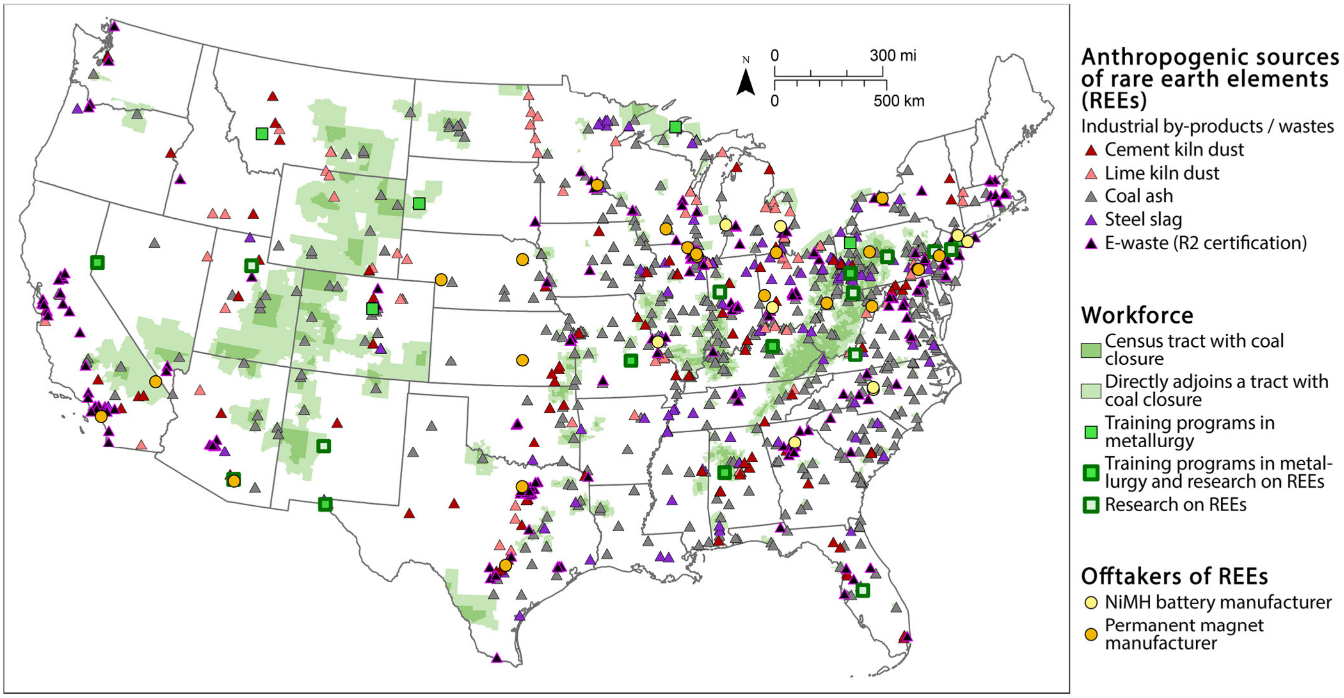
Pennsylvania can be the first mover for the extraction of REEs from industrial wastes, starting with coal ash, and is well positioned to establish a supply chain for REEs (Figure 3). Pennsylvania's historical and more recent energy production and industrial activities can also provide other sources of REEs like steel slag, acid mine drainage, wastewater treatment of production water from oil and gas extraction, and e-wastes. Pennsylvania already has nine e-waste recycling facilities that are R2 certified and located mainly in the Philadelphia region (SERI 2020). The certification ensures a minimal environmental impact and workers safety at recycling facilities.

Main buyers of REEs are manufacturers of permanent magnets and some types of batteries. Permanent magnets, especially Nd-Fe-B magnets can be used for many different applications such as electronics, medical, aerospace, and motors, with manufacturers in Pennsylvania (e.g., Electron Energy Corporation and K&J Magnetics). The largest battery manufacturing facilities do not necessarily need REEs as most batteries for electric vehicles rely mostly on lithium. Though, in some cases, the lithium-ion batteries have REE-coated cathodes, and NiMH batteries contain REEs like La, Ce, Nd, and Pr.

Figure 4 illustrates potential off takers of REEs in the United States and outlines hot spots with large amounts of legacy industrial wastes, and industries that rely on a REE supply, along with training programs on metallurgy that are best positioned to train the future workforce on REE extraction and processing.

With their rich industrial history, states like Pennsylvania, West Virginia, Ohio, Indiana, Illinois, and Michigan look well positioned to develop waste-to-REE supply chains. The stockpiles of industrial waste are sparser in the western United States, but a history of metal mining has led to several metallurgy training programs and acid mine drainage from abandoned mines that could be used as a feedstock.

Figure 4: Waste-to-Product Supply Chain for REEs



REE-bearing industrial wastes, industries relying on REE supply, training programs in metallurgy, research grants on REEs, and communities affected by coal mines and coal power plants closures, that might be able to transfer their skillset in the REE supply chain. Source: Kirchofer et al. 2013; EPA 2023; The White House, n.d.; EarthJustice 2022.

Policy Pathways

To secure a sustainable and economically beneficial domestic supply of rare earth elements, policymakers must prioritize innovative recovery pathways, particularly from abundant industrial wastes like coal ash. Both federal and state governments have a critical role in facilitating this transition. At the federal level, continued support is important to ensure effective deployment of existing federal funding already allocated under the Inflation Reduction Act (IRA) and the Infrastructure Investment and Jobs Act (IIJA) (Rep. Yarmuth 2022; Rep. DeFazio 2021).

These funds, specifically earmarked for research and development into critical mineral recovery, represent significant federal investments into securing domestic REE supplies. Despite ongoing political uncertainty around federal funding priorities, bipartisan acknowledgment of the strategic importance of critical minerals may mitigate political risks, underscoring the necessity for sustained Congressional and Executive support.

At the state level, Pennsylvania offers a uniquely advantageous position due to its extensive coal ash repositories. Policymakers have bipartisan momentum behind proposals that incentivize innovative REE recovery projects. As reporting by Eliza Griswold underscores, such initiatives are not merely environmentally beneficial but can revitalize local economies severely impacted by the energy transition (Griswold 2022), but some uncertainty remains around the ownership of the waste which could slow down projects' deployment (Nguemgaing and Collins 2026).

Pennsylvania's historical industrial base, particularly in metallurgical engineering and mineral processing, aligns naturally with these emerging opportunities. State-supported pilot projects and financial incentives can rapidly demonstrate the viability of coal ash as a source for REE extraction, creating sustainable jobs and providing meaningful community benefits.

Moreover, both state and federal authorities should prioritize regulatory clarity to facilitate permitting while protecting the environment and communities and remediation efforts associated with coal ash extraction projects. Clear and efficient permitting processes can accelerate industry uptake, reduce market uncertainty, and enhance investor confidence, driving quicker deployment of essential infrastructure. By championing coal ash recovery as an economically viable, environmentally strategic, and geopolitically significant resource, policymakers can position the United States—and Pennsylvania specifically—as leaders in the critical minerals supply chain of the future.

Key Policy Recommendations

1. **Protect and Expedite Federal Funding:** Ensure timely allocation and safeguard funding already dedicated under the Inflation Reduction Act (IRA) and Bipartisan Infrastructure Law (BIL) specifically for REE recovery projects from coal ash.
2. **Support State-Level Pilot Projects:** Provide targeted financial incentives and legislative backing for pilot projects demonstrating viable REE extraction from coal ash in Pennsylvania.
3. **Streamline Regulatory Processes:** Clarify and expedite state and federal permitting processes for coal ash remediation and REE extraction, reducing uncertainty and promoting rapid infrastructure deployment, while ensuring environmental and community protection.
4. **Leverage Existing Industrial Expertise:** Foster workforce development programs that capitalize on Pennsylvania's industrial heritage and expertise in metallurgical and mineral processing sectors.

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