



Coal ash resources and potential for rare earth element production in the United States

Robert C. Reedy¹ · Bridget R. Scanlon¹ · Davin A. Bagdonas² · James C. Hower³ · Dennis James⁴ · J. Richard Kyle¹ · Kristine Uhlman¹

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Abstract

The renewable energy industry is heavily reliant on rare earth elements, underscoring the need to develop resources and production. The objective of this work was to estimate coal ash resources and potential for extraction of rare earth elements using data for the US. Data on spatiotemporal variability in coal ash resources and disposition were compiled from various federal databases and rare earth elements levels in ash were compiled from the literature. Results show that ~52 gigatons (Gt) of coal were produced in the US (1950–2021). Power plants account for most of the coal use, particularly since 1980. Coal ash (5.3 Gt) represents a mean of 10% of coal by weight, ranging from 6% for subbituminous to 14% for lignite. About 70% of coal ash is potentially accessible for rare earth element extraction (1985–2021) and was disposed in landfills and ponds with the remaining coal ash used onsite or sold. Median values of total rare earth elements are much higher in ashes derived from the Appalachian Basin (median 431 mg/kg) than in the Illinois (282 mg/kg) or Powder River basins (264 mg/kg). Considering the market value of rare earth oxides, potentially accessible ash volumes, and percent rare earth element extraction (30% Appalachian and Illinois Basins; 70% Powder River Basin) results in an estimated \$8.4 billion value. This study provides fundamental information on accessible coal ash resources in the US, linkages to coal sources, and preliminary estimates of rare earth element levels for future development within the US.

Keywords Coal combustion byproducts · Coal ash · Fly ash · Bottom ash · Rare earth elements · Resource evaluation

Abbreviations

ACAA American Coal Ash Association
CCB coal combustion byproduct(s)
DOE Department of Energy
EIA Energy Information Administration
FERC Federal Energy Regulatory Commission

REEs rare earth elements – lanthanide series
REO rare earth oxides
REEYSc rare earth elements plus yttrium and scandium
USGS US Geological Survey
USD US dollars
Gt gigatons = 10^9 metric tons
Gt/yr gigatons per year
Mt megatons = 10^6 metric tons
Mt/yr megatons per year
TWhr terawatt-hours = 10^{12} watt-hours
mg/kg milligrams per kilogram

✉ Bridget R. Scanlon
bridget.scanlon@beg.utexas.edu

- ¹ Bureau of Economic Geology, University of Texas at Austin, Jackson School of Geosciences, 10100 Burnet Rd., Bldg. 130, Austin, TX 78758, USA
- ² Center for Economic Geology Research, Energy Innovation Center, University of Wyoming, 1000 E. University Ave, Laramie, Wyoming 82071, USA
- ³ Earth & Environmental Sciences, University of Kentucky, 2540 Research Park Dr, Lexington, Kentucky 40511, USA
- ⁴ Dennis James Consulting LLC, 1806 Longwood Ct, Allen, TX 75013, USA

1 Introduction

Rare earth elements (REEs) are critical for many industries, including solar panels, permanent magnets for wind turbines, electric vehicles, and batteries, making them essential for national security and economic prosperity. All 18 REEs (16 in lanthanide series + yttrium + scandium, REEYSc) are

included in the list of critical minerals by the USGS (Federal Register 2022). The US is heavily reliant on imports of REEs from China, increasing the vulnerability of the supply chain. The US Department of Energy (DOE) estimates that current conventional US REEs reserves total 1.4 million tons (Mt); however, unconventional coal sources could provide an additional 11 Mt of REEs (US 2020). The US DOE developed the Carbon Ore, Rare Earth and Critical Minerals (CORE-CM) program to assess the value of US coals and associated byproducts as feedstocks for domestic production of REEs and critical minerals to enhance national and economic security (US DOE, 2021). In addition, coal ash generated from coal combustion in power plants is environmentally sensitive. Coal ash or coal combustion byproducts contain contaminants, such as Hg, Cd, As, and radionuclides, having the potential to contaminate water sources if not properly managed (Zielinski and Finkelman 1997). Therefore, extraction of REEs from coal ash could be used to offset costs of improving management of coal ash impoundments to reduce adverse environmental impacts.

Previous studies indicate that REEs are concentrated by factors of 4–10 times in coal ash from power plants because they are non-volatile and accumulate in the ash during combustion (Franus et al. 2015; Kolker et al. 2023; Scott and Kolker 2019). Therefore, coal ash could serve as a viable resource for REEs (and potentially other critical minerals). A reconnaissance analysis of REEYSc levels in 100 ash samples throughout the US reveals that mean total REEs+Y+Sc is higher for Appalachian coals (591 mg/kg) relative to Illinois coals (403 mg/kg) and Powder River Basin coals (227 mg/kg) (Taggart et al. 2016). Ashes from the different coal basins have different REE signatures (Hower et al. 2021). REE speciation and modes of occurrence in coal ash are also important and affect extractability

of REEs from coal ash (Fu et al. 2022; Liu et al. 2019; Pan et al. 2018).

The disposition of coal combustion products includes onsite use and sales to produce aggregate, cement, road building materials, and gypsum. The remaining byproducts are generally disposed of in landfills or ponds. If a power plant is located adjacent to a mine, particularly a surface mine, often termed “mine-mouth” power plant, products may be used for back-fill in mined areas.

The objective of this study was to estimate spatiotemporal variability in coal ash amounts that have been generated historically and that might currently be accessible as a resource of REEs and other critical minerals. A secondary objective was to evaluate REE levels in different ash deposits from the literature to assess the potential value of ash deposits as an REE resource. Ash resources were linked to the mine source. We are not aware of any similar compilation of ash resources for the US as a whole. The source of coals and related ranks for power plants changed over time in some regions making it difficult to link coal ash in power plants to mining and coal rank. Analysis of REE extraction processes is beyond the scope of this analysis and is not sufficiently mature at this time to provide a reliable report.

A comprehensive approach was used to understand the evolution of coal ash resources. The most comprehensive information is available for the 1985–2021 period, including power plants, coal deliveries, and ash disposition. Variability in coal ash production was evaluated using this detailed information and percentages used to extend the time series back to 1950. The source and mass of the ash resources was estimated. Ash disposition was also quantified to determine the ash resources that are potentially available for REE extraction. Data on representative REE levels in different coal ash deposits were compiled to better understand the potential for REE development from these ash resources. Because of the highly interconnected nature of coal ash requiring linkages to mining, coal rank, transport to power plants, and ash disposition, this comprehensive assessment of coal ash resources provides a necessary first step to understanding coal ash resources for potential REE development in the US and provides a template for quantifying similar resources globally.

2 Methods

A flow chart describes the various data sources and linkages in the study (Fig. 1). This study is based primarily on data from two main sources: the United States Geological Survey (USGS) and the US Energy Information Administration (EIA). The EIA data include archived information originally collected by the Federal Energy Regulatory

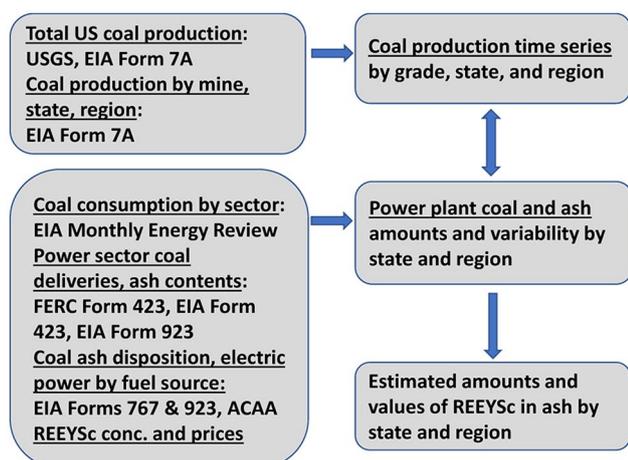


Fig. 1 Workflow showing data sources and linkages between coal mine data, power plant data, REEYSc levels and prices to determine estimated amounts and values of REEYSc in ash

Commission (FERC). Results of this study were compared in part with data from the American Coal Ash Association (ACAA 2015, 2021). Concentrations of REEs in coal ash were compiled from literature.

The scale, content, and completeness of archived EIA power plant and coal mining data varied through time. We analyzed the available datasets and results for selected datasets were used to estimate values during periods outside their specific data ranges. National coal consumption data by sector began in 1950. Detailed coal and associated ash content deliveries to power plants began in 1972, detailed coal production data began in 1983, and detailed disposition data on coal combustion byproducts began in 1985. Supporting figures and tables are referenced in this article with the prefix “S” followed by the figure or table number and are provided with the paper.

Coal and ash values in this study are reported in metric ton units (1 metric ton = 1000 kg). Annual total US coal production data by basin and rank (i.e., bituminous, subbituminous, and lignite) were compiled from the USGS during 1800–1982 and EIA Form 7 A during 1983–2021. The data were also summarized to evaluate production at the state and basin scales. These data sources do not include information regarding coal ash content. Data on coal consumption by sector (e.g., electric power, industry, etc.) and net electricity generation by fuel source were compiled from EIA. Temporal variability in net electricity generation for all fuel sources was also summarized, including coal, nuclear, natural gas, wind, etc.

Ash content represents the non-combustible portion of coal that is generated upon combustion, collectively termed coal combustion byproducts (CCBs), that is expressed as a weight% of the coal. We estimated ash content based on reported values for monthly coal deliveries to power plants recorded on FERC Form 423 during 1972–2001, combined data from FERC and EIA Form 423 during 2002–2007, and EIA Form 923 during 2008–2021. Note that there are small discrepancies between annual total amounts of coal delivered to power plants and amounts of coal actually consumed by the power plants. Additionally, the power plant data do not represent total amounts of coal produced in the US. However, if it is assumed that the ash contents of coal delivered to power plants are representative, then the total national amount of ash associated with coal production can be estimated from the weighted mean ash content derived from the power plant data. These data also provide a basis for examining year-over-year variability of ash content in coal production at the state and basin scales. The ash content analysis was performed for data during 1972–2021 (Fig. S1).

The CCBs include fly ash, bottom ash, clinker or slag, and various other products, particularly gypsum used for

wallboard, and are based in part on the specific nature of sulfur-removal technology being used. This study focuses on CCBs categorized as fly ash and bottom ash. During 1985–2005, US power plants reported the categorical disposition of CCBs on EIA Form 767. These data were not recorded for 2006–2007. Beginning in 2008, these data were reported on Schedule 8 of EIA Form 923 (EIA 2022c). Disposition categories include amounts and types of CCBs sold, used, stored, and disposed, either onsite or offsite. Disposal is in either dry landfills or wet landfills (ponds). Varying percentages of the fly and bottom ash are sold to the aggregate and road building industries. These quantities are consumed by those industries and are therefore not generally accessible as a potential resource for REEs. However, the fly and bottom ash that was disposed of in landfills or placed in storage is potentially accessible as a resource.

Estimates of REE concentrations in coal fly ash and bottom ash were compiled from the literature. Data on REE content in coal combustion fly ashes are described from many basins throughout the US and were compiled in Taggart et al. (2016). These samples were collected between 1994 and 2015 from 22 coal-fired power plants mostly in the Appalachian, Illinois, and Powder River basins. Comprehensive REE analyses for coal ash deposits in the Powder River Basin were compiled from samples collected from four coal-fired power stations over varying time periods by Bagdonas et al. (2019). REE concentrations were summed for the lanthanide series (15 elements) and additionally yttrium and scandium.

3 Results and discussion

3.1 Historical coal production and use

In 2021, the US had an estimated 11.2 Gt of technologically and economically recoverable coal reserves (EIA 2021). This excludes resources in areas that have not yet been evaluated. Coal rank varies by basin across the US (Fig. 2). Bituminous rank coal is primarily located in the central and eastern basins of the US and in the Uinta Basin, with subbituminous rank coal in the Rocky Mountain states, and lignite rank coals in the Gulf Coast and Ft. Union basins (Fig. 2). For this study, data were aggregated for the Rocky Mountain state basins and referred to collectively as Western basins, excluding Powder River Basin data where available.

Coal production varied over time in the US (Fig. 3) (EIA 2021; Milici 1997). Between 1912 and 1960, coal production averaged 0.48 Gt/yr (range: 0.31–0.61 Gt). After 1960, annual production increased steadily, peaking in 2008 at 1.06 Gt, and then declined afterwards to 0.52 Gt by 2021. A total of 78 Gt of coal were produced in the US during

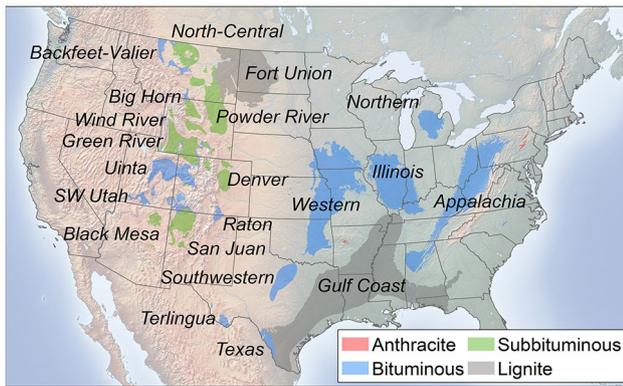


Fig. 2 Locations of coal producing basins in the US symbolized by predominant coal rank. Basins in the Rock Mountain region, excluding the Powder River Basin and Fort Union Basin, are collectively referred to as Western basins in this study, whereas the Western Basin proper is included in the Interior basins category. Not all basins actually produce coal

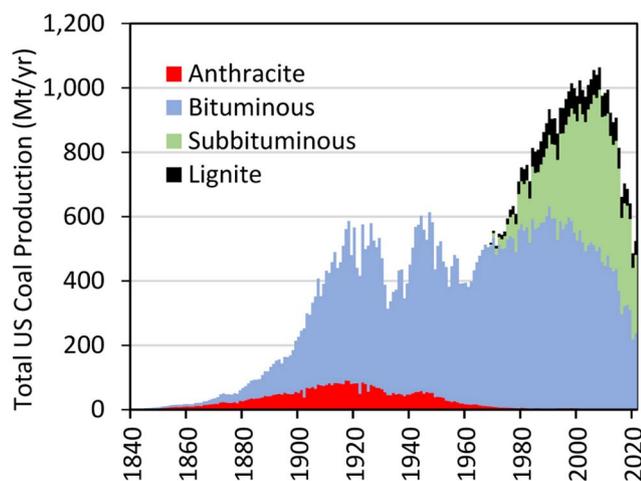


Fig. 3 Historical coal production by rank in the US based on USGS data prior to 1949 and EIA data beginning in 1949. Data are provided in Table S1

1800–2021, with about 70% produced since 1950 (52 Gt). Production by rank includes 7% anthracite, 76% bituminous, 18% subbituminous, and 4% lignite over the entire period. The total amount of coal produced is 7× the current recoverable coal reserves at recently producing mines of 11.2 Gt estimated by the mining industry (EIA 2021). If no new US reserves are established and production continues at current rates of about 0.5 Gt/yr, existing recoverable coal reserves at recently producing mines will be exhausted in about 25 years.

Prior to about 1970, production consisted almost entirely of bituminous rank coal with dwindling and relatively minor amounts of anthracite, which peaked in production during the early 1900s (Milici 1997). Beginning in the 1970's, the use of lower rank coals began to increase, including

subbituminous coal, primarily from the Powder River Basin in Wyoming along with other Western basins, and lignite, primarily from Gulf Coast states and North Dakota. At the peak of US coal production in 2008, the rank distribution consisted of 47% bituminous, 46% subbituminous, 6.5% lignite, and 0.1% anthracite (Fig. 3) (EIA 2021).

The dominant source of coal production prior to about 1900 was from the Appalachian Basin (84% of total coal production), followed by the Illinois Basin (12%), and Western basins (3%) while the Gulf Coast and Fort (Ft.) Union basins combined represented only 0.2% (Milici 1997). Between 1900 and 1971, production shifted westward somewhat, with 77% of total production from the Appalachian Basin, 18% from the Illinois Basin, and 4% from Western basins, with continued minor contributions (0.5%) from the Gulf Coast and Ft. Union basins. During 1972–2021, 31% of total production was from the Appalachian Basin, 14% from the Illinois Basin, and 46% from Western basins combined with the Powder River Basin, with increased contributions (8%) from the Gulf Coast and Ft. Union basins.

In addition to production, the US also imports relatively small amounts of coal from other countries. In this analysis, imported coal is presumed to be entirely consumed. Net US coal consumption therefore consists of production increased by imports and reduced by exports. Since 1950, total US coal consumption accounted for an average of 92% of total US production, ranging from 83% to 102%, with net exports accounting for the difference (Fig. S2) (EIA 2022b; EIA 2022d). Consumption briefly exceeded production in 2000 and 2003. Annual exports varied during 1950–2021 with no overall trend, averaging 8.8% of annual production (range: 1.2% [2006] to 15.5% [1957]). Recently (2011–2021), exports have averaged 11.5% of total production. Imports have consistently remained low overall, averaging 1.7% during 2000–2021.

During 1950–2021, total US coal consumption was 47.7 Gt relative to 51.7 Gt total production during that time and 37.4 Gt (79%) was consumed by electric power plants. In 1950, coal was consumed generally evenly across several sectors, with electric power becoming dominant by about 1955 (Fig. 4). Consumption by the power sector steadily increased, reaching 81% by 1980, and averaging 92% after 1998 (range: 91%–94%) (EIA 2022a).

3.2 Electric power generation

Total US net electricity generation increased by a factor of 13 from 329 terawatt hours (TWh) in 1950 to 4135 TWh in 2007. Since 2007, total net generation has remained relatively constant. During 1950–2008, coal represented an average of 52% of annual total US electricity generation,

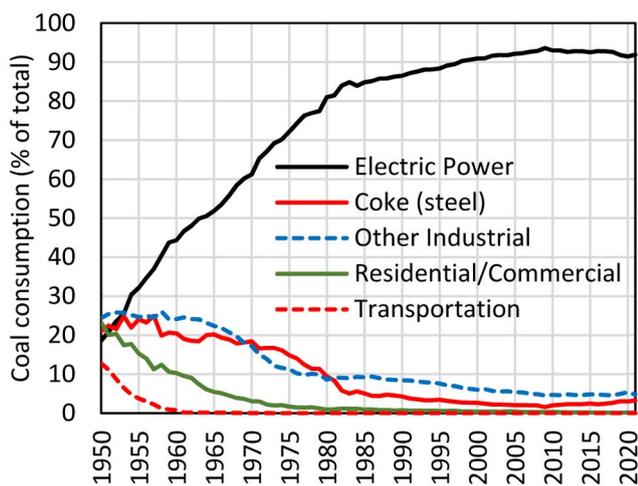


Fig. 4 US coal consumption by sector. Data are provided in Table S3

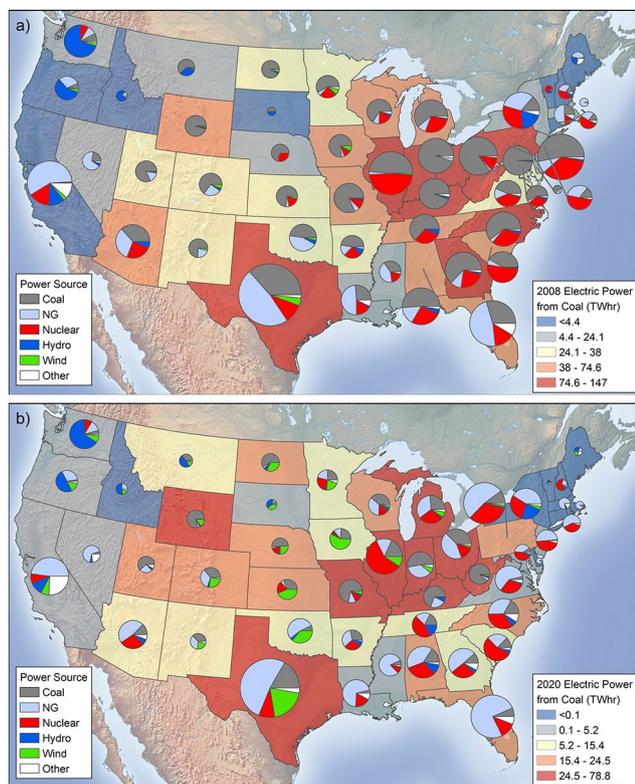


Fig. 5 Distribution of electric power generation (TWhr) by fuel source (pie charts) and by coal (color shading) at **a** The peak of coal production in 2008 and **b** in 2020. Pie chart sizes are proportional to total electrical generation in each state. The states are color-shaded based on the amount of US total electrical power from coal for 2008. Data are provided in Table S4b. A similar map for 1990 is shown in Fig. S4

declining to 21% by 2021 (Fig. S3). Natural gas generation averaged about 20% prior to 1970, declined to 10% by 1990, and then grew steadily to 38% by 2021. Nuclear generation increased from 1% in 1970 to 20% in 1991 and remained stable thereafter. Hydroelectric generation

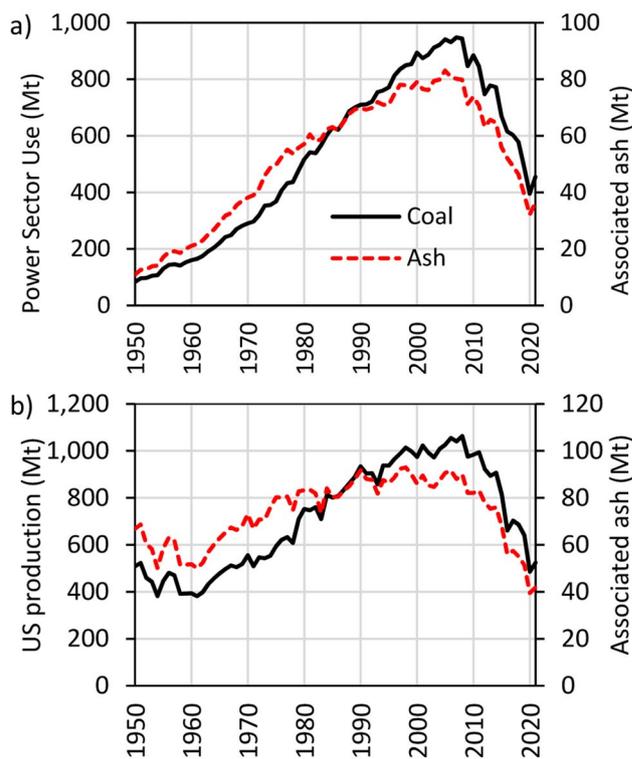


Fig. 6 Historical US **a** Total reported power plant coal consumption (37.9 Gt) and estimated associated ash (3.71 Gt), and **b** Reported total US coal production (51.7 Gt) and estimated total associated ash (5.30 Gt). Ash values are based on coal and associated ash contents delivered to power plants and reported on FERC Form 423 (1972–2007), EIA Form 423 (2002–2007), and EIA Form 923 (2008–2021). Values for ash prior to 1972 are estimated from the 1972–1977 power sector mean ash content (13.1%). Data are provided in Table S5

decreased steadily from about 25% in the early 1950s to 6% by 2021. Wind generation increased after 2006 reaching 9% by 2021 (EIA 2022c). All other sources combined (petroleum, solar, biofuels, and geothermal) represent 5% of generation from 1950 to 2021, though petroleum briefly reached 17% in the 1970s.

Coal production and related electricity generation peaked in the US during 2003–2008. Snapshots of energy sources and relative amounts of coal used for electric power generation by state are shown for 2008 and 2020 (Fig. 5). Coal use for electric power shows generally consistent distribution through time, and is most prominent in the upper Mid-West, Texas, and various states in the Southeast.

3.3 Power plant coal and ash

Total coal consumed by power plants increased gradually from 0.08 Gt in 1950 to 0.93 Gt/yr in 2003–2008 and steadily decreased to 0.4 Gt in 2021 (Fig. 6a). The national weighted mean total ash content averaged 13% during 1972–1977, declined to 10% during the late 1980s, and steadily declined

thereafter to 8% by 2018–2021 reflecting increased used of low-ash content Powder River Basin subbituminous coal and diminishing use of high-ash content Gulf Coast lignite (Table S5). A total of 37.9 Gt of coal were consumed by power plants during 1950–2021, with associated ash of 3.71 Gt (9.8%), assuming a mean ash content of 13.1% prior to 1972. Applying the time-series of annual mean ash content values of coal delivered to power plants to total US coal production (51.7 Gt) results in an estimated 5.3 Gt (10.2%) of associated ash (Fig. 6b).

Coal was delivered to power plants from seven US basins or groups of basins during 1972–2021 and mean ash contents were generally consistent by basin (Fig. S5a). The top four coal producing regions, including the Appalachian, Powder River, Illinois, and Western basins, accounted for 90% of all delivered coal and 86% of associated ash during that period. Mean bituminous coal ash was similar in the Appalachian Basin (11.3%) and Illinois Basin (10.3%) while mean subbituminous coal ash was half of that in the Powder River Basin (5.3%). The collective Western bituminous and subbituminous basins generally had mean ash contents of 10%–10.5%, respectively. Mean ash content of lignite from the Gulf Coast Basin (16.2%) was much greater than Ft. Union Basin lignite (9.5%). Interior bituminous basins also had high ash content (16.3%).

State level data for 1990–2021 indicate that coal was produced from 26 states. Wyoming was by far the highest producing state (9.25 Gt), followed by Kentucky (2.56 Gt), West Virginia (2.26 Gt), and Texas (1.19 Gt) (Fig. S6a). The top ten producing states combined delivered 86% of coal and 84% of associated ash.

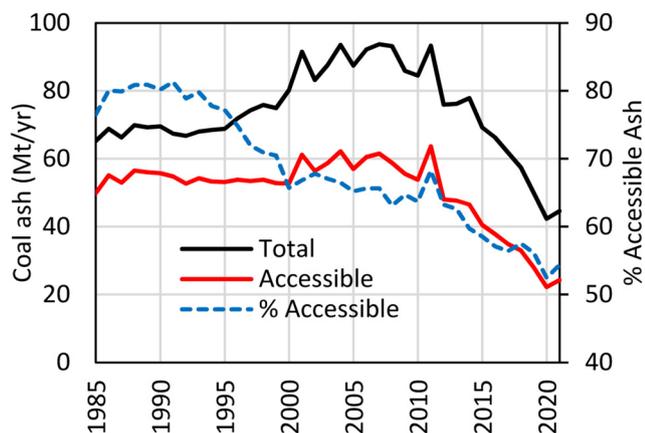


Fig. 7 Total and potentially accessible coal ash reported by the electric power sector during 1985–2021. Data are provided in Table S8. Data for 2006–2007 were not collected and are interpolated based on mean percentages for recorded data during 2001–2012

3.4 Spatiotemporal variability of ash content in coal

Interannual variability (i.e., standard deviation) of mean ash content delivered from most basins was low to moderate during 1972–2021. The lowest variability was for Powder River Basin subbituminous coal ($\pm 0.2\%$), though production data for that basin were not separated from other Western subbituminous basins prior to 1990. The major eastern basins also had low variability, including the Appalachian Basin ($\pm 1.3\%$) and Illinois Basin ($\pm 1.0\%$) (Fig. S5b). Lignite ash content in the Ft. Union Basin was very consistent ($\pm 0.5\%$) and moderate in the Gulf Coast ($\pm 2.0\%$). Interannual ash variability for 23 producing states during 1990–2021 ranged from $\pm 0.1\%$ to $\pm 2.0\%$ (mean $\pm 0.9\%$), representing 98.4% of coal and 97.9% of associated ash supplied to all power plants during that period (Fig. S6b). Ash contents from states with higher interannual variability, including Arkansas, Oklahoma, and Virginia, range from $\pm 5.5\%$ to $\pm 9.9\%$ ash content, but represented only 1.6% of all delivered coal and 2.1% of the associated ash for that period. These results suggest that associated ash content at the producing basin and state scales generally remained consistent through time.

3.5 Coal ash disposition

Total reported ash disposition during 1985–2021 was 2547 Mt. Interpolated values for missing data during 2006–2007 increase the total to 2733 Mt (Fig. 7), which is about 10% greater than the reported total associated ash content of delivered coal during the same period (2494 Mt, Table S5). Annual amounts of coal ash accounted for by US power stations remained fairly stable during 1985–1995, averaging 68 Mt per year, increased erratically to about 89 Mt/yr during 2001–2011, and declined sharply thereafter to 45 Mt in 2021. Bottom ash accounted for 25% and fly ash for 75% of the total (Fig. S7).

About 69% (1873 Mt) of all ash generated in the US during 1985–2021 is potentially accessible for evaluation as an REE resource, having been disposed of in landfills (33%), ponds (20%), and offsite disposal facilities (13%), or placed in storage (2%) (Fig. S8a). The remaining 31% of ash (860 Mt) was either sold (22%) or otherwise used for some purpose (9%) (Fig. S8b). The annual amount of potentially available ash was not stable through time and declined steadily from about 80% during 1985–1992 to about 55% by 2021 (Fig. 7), reflecting progressively increased beneficial uses of ash by industry. If it is assumed that 80% of ash produced annually prior to 1985 is potentially available, the total amount of potentially accessible ash generated at power plants during 1950–2021 is estimated to be

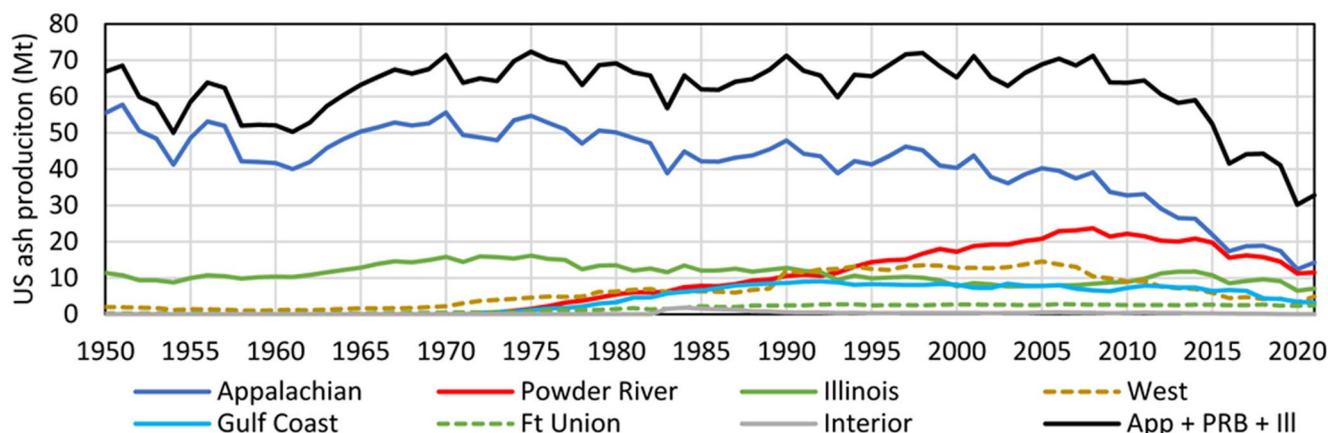


Fig. 8 Estimated total associated ash from coal production in the US by basin. About 83% of all ash produced during the period was from the Appalachian (App), Powder River (PRB), and Illinois (Ill) basins combined. Data are provided in Table S13

Table 1 Summary of associated coal ash deliveries by destination basin and percentages of ash mined within that basin for 1972–2021 as reported on FERC Form 423, EIA Form 423, and EIA Form 923. An expanded version of this table is provided in Table S15b. Associated ash for all imported coal was 19.8 Mt

Destination Basin	Delivered Ash		Mined in Basin
	(Mt)	(% of Total)	(%)
Appalachian	1278.1	43.7	80.8
Powder River	124.8	4.3	30.6
Illinois	296.2	10.1	75.0
Western	396.1	13.6	88.4
Gulf Coast	425.9	14.6	27.2
Ft. Union	86.3	3.0	96.4
Interior	314.1	10.8	7.2
Total	2921.5	100.0	63.8

2.7 Gt (Table S9a). Based on the 1985–2021 data, there are 46 states with some amount of accessible ash (Fig. S9b), though the top half (23 states) account for 83% of the total.

3.6 Comparison with American Coal Ash association data

The American Coal Ash Association (ACAA) maintains annual estimates of CCBs generated since 1974 (Fig. S10) (ACAA 2015, 2021). A primary goal of the ACAA is to provide information on the various beneficial uses of CCBs and the amounts used by non-power plant sectors. A summary of the ACAA data indicates that total ash byproducts generated by power plants during the period 1974–2021 was about 3.1 Gt (Table S11), in agreement with the 3.1 Gt of ash delivered to power plants estimated in this study for the same period (Table S5). The ACAA also estimates that 1.11 Gt (35%) were used beneficially during that period and are therefore inaccessible for REE extraction, resulting in 1.99 Gt (64%) of potentially accessible ash during 1974–2021.

Power plant ash amounts accounted for in this study during 1985–2021 totaled 2733 Mt with 1873 Mt (69%) potentially accessible in landfills or storage (Table S8), which is slightly greater than the corresponding ACAA values for the same period for total ash of 2,597 Mt and accessible ash of 1,565 Mt (60%) (Table S10).

3.7 Rare earth element levels in coal ash

Literature results for REEYSc levels show variations among coal basins, consistent with previous findings (Taggart et al. 2016). Most (93%) of the data reflect samples from the Powder River Basin (105 samples), the Appalachian Basin (65 samples), and the Illinois basin (41 samples) (Table S12a). Mean values of REEYSc are highest in Appalachian coal ash (585 mg/kg) and lowest in Powder River Basin coal ash (330 mg/kg) (Table S12b, Fig. 8). Internal variability in REEYSc in coal ash from within the coal basins is low, with standard deviations of 144 mg/kg (Appalachian), 86 mg/kg (Illinois), and 67 (Powder River). Although the REEYSc levels are lower in the Powder River Basin, REE extraction rates are much higher (70%) than those from ashes from Appalachian Basin and Illinois Basin coals (30%), which is attributed to the higher calcium levels in the Powder River Basin ashes (Bagdonas et al. 2022; Burgess et al. 2024).

3.8 Regional sources and destinations of coal ash delivered to power plants

Annual and cumulative amounts of coal ash produced by source mine basin were summarized by destination state and by source basin associated with the destination states and basins based on data from FERC/EIA Form 423 (1972–2007) and EIA Form 923 (2008–2021) (Table S15). The total amount of associated ash delivered to each state was not fully reported for the period prior to 2008. However, the

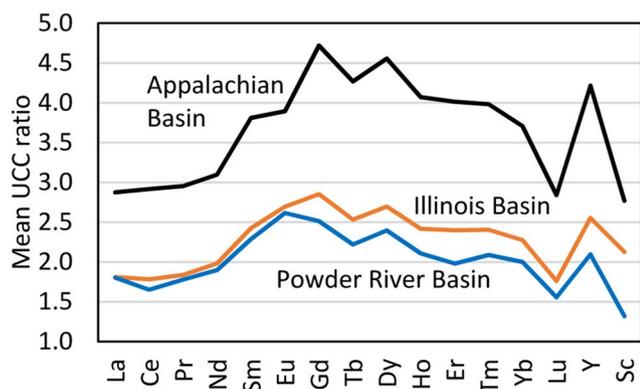


Fig. 9 Mean REEYS Sc concentration ratios in coal ash derived from the Appalachian, Powder River, and Illinois basins. Data are provided in Table S12c

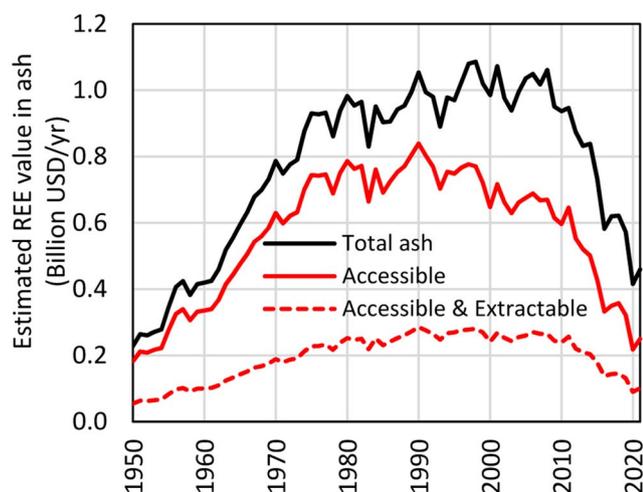


Fig. 10 Estimated value of rare earth elements (REEs) in ash derived from combined Appalachian, Powder River, and Illinois basin coal delivered to US power plants during 1950–2021 based on 2020 rare earth oxide prices. Curves are shown for the total, potentially accessible, and potentially accessible and extractable REEs values, with period estimated total values of \$56 billion, \$41 billion, and \$14 billion, respectively. Data are provided in Table S14b

data account for 2.93 Gt (92%) of the estimated total of 3.19 Gt of ash delivered to all US power plants from US coal mines during 1972–2021 (Table S6).

Power plants in the Appalachian Basin received 1278 Mt, representing 44% of total ash delivered to all states (Table 1). The Gulf Coast received 426 Mt (15%) and the collective Western basins received 396 Mt (14%). Regions receiving the least amount of ash include the Powder River Basin (125 Mt, 4%) and the Ft. Union Basin (86 Mt, 3%). At the state level, the top 10 destination states account for 1.8 Gt (62%) of total ash delivered to all states (Table S15b). Texas ranked number one with 327 Mt (11%), including 103 Mt of ash sourced from Gulf Coast (lignite) mines. The top five Appalachian Basin states (Kentucky, West Virginia,

Ohio, Pennsylvania, and Alabama) collectively accounted for 938 Mt (32%).

In general, most of the associated ash mined in a given region was delivered to power plants in that region, including the Appalachian Basin (81%), Illinois Basin (75%), collective Western basins (88%), and Ft. Union Basin (96%) (Table 1). Exceptions include the Powder River Basin (31%) and the Gulf Coast (27%).

3.9 Estimated rare earth element values

Annual coal and associated ash production data were summarized at the mine basin level (Table S13). Ash derived from coals that were mined in the Appalachian, Illinois, and Powder River basins combined accounted for 85% of the US total production for the period 1950–2021 (Fig. 9). Based on mean concentrations for ash samples from these basins, the percentages of coal used by the US power sector, and 2020 rare earth oxide (REO) market prices, the total amount of REO is 1.97 Mt with an estimated value of \$56 billion for all coal ash delivered to power plants from these basins during 1950–2021 (Fig. 10, Table S14). The value of potentially accessible ash in landfills, ponds, or storage is \$41 billion. Current REE extraction technology efficiencies of 30% for Appalachian and Illinois basin ashes and 70% for Powder River Basin ashes (Taggart et al. 2016) reduce the net REE value to \$14 billion. Including Y and Sc increases the amount to 2.62 Mt and at total extractable value to \$165 billion (Table S14).

Based on power plant coal delivery and ash disposition data, the combined ash at US power plants from the Appalachian, Illinois, and Powder River basins represents 70% of the ash accounted for during 1972–2021. The estimated total 2020 REE oxide value of that ash is \$33 billion for all power plants with ash from these regions (Table 2). Based on an overall potential accessibility of 69% for this period and the noted REE extraction efficiencies, the estimated total 2020 REE oxide value is reduced to \$8.4 billion.

Most of the ash is located in landfills associated with power plants within the Appalachian (\$4.9 billion, 58%), Interior (\$1.5 billion, 17%), and Illinois (\$0.9 billion, 11%) basins. Including Y and Sc increases the total accessible and extractable value to \$97 billion (Table S15c). This analysis does not include the value of the remaining 30% of accounted for ash from other basins, including significant amounts of lignite ash in the Ft. Union and Gulf Coast states where lignite represents 96% and 27%, respectively, of the total power plant ash in those regions.

Table 2 Estimated 2020 REO values in coal ash by source and destination basins and quantities of ash evaluated and not evaluated for REO values during 1972–2021. Accessible represents 69% potentially accessible ash resources and extractable represents REO extraction efficiencies of 30% for Appalachian and Illinois basin ash and 70% for Powder River Basin ash. An expanded version of this table is provided in Table S15c

Destination basin	Estimated REEs oxides values by source basin (Billion USD)					Ash from all basins	
	Appalachian	Powder River	Illinois	Total	Accessible & Extractable	Evaluated (Mt)	Not Evaluated (Mt)
Appalachian	20.2	0.43	2.30	22.89	4.86	1251.6	26.5
Powder River	-	0.44	-	0.44	0.21	38.1	86.7
Illinois	0.2	0.66	2.80	3.66	0.94	289.7	6.5
Western	-	0.52	-	0.52	0.25	45.5	350.7
Gulf Coast	0.5	0.98	0.32	1.83	0.65	137.8	288.1
Ft. Union	-	0.04	-	0.04	0.02	3.1	83.2
Interior	0.5	2.77	0.14	3.36	1.46	275.0	39.1
Total	21.3	5.84	5.55	32.74	8.39	2040.8	880.8

3.10 Implications for future work

This reconnaissance analysis provides an overview of coal ash produced by power plants from coal mined in different basins and the disposition of that ash, emphasizing potentially recoverable ash resources. Linking the data on ash resources to current estimates of REEYSc concentrations in ash from different basins along with the market values provides initial estimates of the value of the ash resources. These data provide a foundation for future work to develop REEYSc resources from coal ash deposits that could potentially offset remediation of ash landfills and ponds to reduce adverse environmental impacts.

The current status of coal ash landfills and ponds should be determined in terms of reclamation because of regulatory issues regarding REEs in landfills that have been fully reclaimed. Because of the current emphasis on environmental impacts from unlined ponds (Earthjustice 2022), future work should consider ranking unlined pond areas according to potential environmental impacts, such as proximity to surface water or depth to groundwater etc. Ranking could also consider environmental justice concerns of impacted communities, which is also extremely important. The economic value that could be obtained from recovering REEYSc from these ashes could help offset, at least partially, remediation costs.

The mode of occurrence of REEYSc in coal ashes derived from coals of different ranks should be determined because this will affect extractability. Data from the Powder River Basin suggest that extractability of REEYSc is moderately high, attributed to high Ca levels in the ashes (70% rate of extraction) relative to ashes from other basins. REEYSc in ashes from Appalachian and Illinois basin coals are Si-Al glass and are fairly difficult to extract (30% rate of extraction).

In order to move this process forward, pilot plants would need to be established to extract REEs from the ashes.

Landfill materials composed of different fly ash and bottom ash products would require extractability experimentation to best understand up-scaling of REE extractive processes. For example, Appalachian basin derived materials would differ in extractability and process to those contributed from the Powder River Basin. Current projects are underway to determine efficient extractability processes for specific materials. In the Powder River Basin for example, the National Energy Technology Laboratory (NETL) is currently working toward a pilot-scale operation (NETL 2020; Stuckman et al. 2019) based upon technology up-scaling from bench-scale successes. Successful up-scaling of extractive methods have also been achieved with Appalachian-based fly ash (Hower et al. 2020).

Extraction methodology developed at lab- to bench-scale for each regional coal byproduct type would provide a catalog of potential pathways for technology scale-up. Depending on regional importance and potential ranking of considerations as described above (environmental impact, environmental justice/social justice considerations, etc.), pairing of technology with resources could be done relatively quickly. Successful laboratory results in one region could also be matched with similar coal byproducts in another region. An example would be results from an Appalachian based resource (Bauer et al. 2022; Hower et al. 2022) being applied to similar materials identified in another region. Consideration of downstream supply chain needs would provide an additional filter for site selection and resource-to-extractive technology planning. With an extractive technology catalog in place, an emerging market within a particular region need only select the coal byproduct landfill that best fits immediate demand.

Finally, this study highlights the significant potential for coal ash development as an REE resource globally. Global annual coal production between 2010 and 2022 was about 8 Gt/yr (IEA 2022). Assuming 10% ash content results in about 1000 Mt of global coal ash generation during that period alone. Global demand for electric generation is

projected to increase by 2.8% annually through 2025. Many nations have historically used and/or will continue to use coal as a major energy source of electric power generation, particularly China, India, and the European Union where ash resources may represent a significant REE resource.

4 Conclusions

Rising interest in developing sources of REEs within the US to enhance security has resulted in increasing focus in evaluating coal and coal combustion products as potential sources of REEs. This study focused on spatiotemporal variability in coal ash generated at power plants as a source of REEs. Coal production doubled from 1950s (0.45 Gt/yr) to late 2000s (1.04 Gt/yr) but reduced to half within the past decade (0.52 Gt 2021). Most (79%) of the US coal consumption has been for power generation (1950–2021). Coal accounted for about 50% of power generation from 1950 to 2005 but decreased to 20% by 2021. A total of 52 Gt of coal was produced (1950–2021) and associated ash represents about 10% of coal production (5.8 Gt). Burning coal in power plants concentrates REEs by factors of 4 to 10, enhancing the value of ash as a source of REEs. An estimated 69% of ash is considered potentially recoverable (1985–2021) as it was stored in landfills and ponds on and offsite whereas the remaining 31% was sold and used by other industries. The Powder River Basin in Wyoming accounted for about 44% of US coal production and almost 27% of associated ash since 2000. Most coal that is produced from a specific basin is also consumed within that region with the major exception of the Powder River Basin which exports most of its coal to other states. Using mean REE concentrations in coal ash derived from major coal basins (Appalachian, Illinois, and Powder River Basin, 85% of US production 1950–2021), the potentially recoverable ash content (68% of total), varying extraction rates (30% for Appalachian and Illinois basins and 70% for Powder River Basin), and 2020 REO market prices resulted in an estimated potential value of REEs in ash of about \$8.4 billion. Including yttrium and scandium increases the estimated value to \$97 billion. In addition to enhancing energy security in the US through development of REE resources, the economic value of producing these REEs could help offset the costs of remediation of unlined ash landfills or ponds in environmentally vulnerable areas. The potential for REE resource development from coal ash should be evaluated globally in nations where coal ash is available.

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Data availability All data related to this study are provided in Supporting Information which includes 11 additional figures and 15 additional tables.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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References

- ACAA (2015) Production and Use of Coal Combustion Products in the US, Historical Market Analysis 2015. American Coal Ash Association, <https://aca-usa.org/publications/ree-publications/>
- ACAA (2021) Production and Use of Coal Combustion Products in the US, Annual Survey Results 2014–2020. American Coal Ash Association, <https://aca-usa.org/publications/production-use-reports/>
- Bagdonas D, Nye C, Phillips E (2019) Rare Earth Element Occurrence and Distribution in the Powder River Basin Coal Core, Wyoming, 2019 Intl. Pittsburgh Coal Conference, Sep. 3–6, 2019., Pittsburgh, Pennsylvania
- Bagdonas DA, Enriquez AJ, Coddington KA, Finnoff DC, McLaughlin JF, Bazilian MD, Phillips EH, McLing TL (2022) Rare earth element resource evaluation of coal byproducts: a case study from the Powder River Basin, Wyoming. *Renew Sustain Energy Rev* 158:112148
- Bauer S, Yang J, Stuckman M, Verba C (2022) Rare earth element (REES) and critical Mineral fractions of Central Appalachian

- Coal-Related Strata determined by 7-Step sequential extraction. *Minerals* 12:1350. <https://doi.org/10.3390/min12111350>
- Burgess W, Chiu CF, Cain T, Roth E, Keller M, Granite E (2024) Extractability indices for screening coal combustion byproduct feedstocks for recovery of rare earth elements. *Int J Coal Geol* 281:104401
- Earthjustice (2022) Mapping the Coal Ash Contamination. <https://earthjustice.org/features/coal-ash-contaminated-sites-map>
- EIA (2022a) Total energy. Annual Energy Rev. <https://www.eia.gov/totalenergy/data/annual/>
- EIA (2022d) Total Energy Data Viewer. <https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T06.01#/?f=M&start=197301&end=202208&charted=0-5-8>.
- EIA (2022c) Electricity, Historical State Data EIA-923 Power Plant Operation Report, <https://www.eia.gov/electricity/data/state/>
- EIA (2022b) Coal data. <https://www.eia.gov/coal/data.php>
- EIA (2021) Annual Coal Report 2020. US Energy Information Agency, Department of Energy, https://www.eia.gov/coal/annual/archive/0584_2020.pdf
- Federal Register (2022) 2022 Final List of Critical Minerals. Federal Register, vol. 87, FR 10381–10382, Doc. No. 2022–04027
- Franus W, Wiatros-Motyka MM, Wdowin M (2015) Coal fly ash as a resource for rare earth elements. *Environ Sci Pollut Res Int* 22:9464–9474
- Fu B, Hower JC, Zhang W, Luo G, Hu HY, Yao H (2022) A review of rare earth elements and yttrium in coal ash: content, modes of occurrences, combustion behavior, and extraction methods. *Prog Energy Combust Sci* 88:100954
- Hower J.C., Groppo J.G., Joshi P., Preda D.V., Gamliel D.P., Mohler D.T., Wiseman J.D., Hopps S.D., Morgan T.D., Beers T., Schrock M. (2020) Distribution of Lanthanides, Yttrium, and Scandium in the pilot-scale beneficiation of fly ashes derived from Eastern Kentucky coals. *Minerals* 10:105
- Hower JC, Groppo JG, Hsu-Kim H, Taggart RK (2021) Signatures of rare earth element distributions in fly ash derived from the combustion of Central Appalachian, Illinois, and Powder River basin coals. *Fuel* 301:119990
- Hower JC, Kolker A, Hsu-Kim H, Plata DL (2022) Rare earth elements in coal combustion fly ash and their potential recovery. In, Karamalidis, A.K. and Eggert, R.G., eds., Rare earth elements and their sustainable extraction from secondary sources, Wiley-AGU Geophysical Monograph Series. In press. <https://doi.org/10.1002/essoar.10510791.1>
- IEA (2022) International Energy Agency Coal 2022 Analysis and forecast to 2025, <https://www.iea.org/reports/coal-2022>
- Kolker A, Lefticariu L, Anderson ST (2023) In: Alvin MA, Murty Y, Lifton J (eds) Energy-related rare earth element sources. *Rare Earth Industry Status and Prospects*, Springer Nature
- Liu P, Huang RX, Tang YZ (2019) Comprehensive understandings of Rare Earth element (REES) speciation in coal fly ashes and implication for REES Extractability. *Environ Sci Technol* 53:5369–5377
- Milici RC (1997) The CoalProd Database: Historical Production Data for the Major Coal-Producing Regions of the Conterminous United States. US Geological Survey, Open File Report 97–447
- NETL (2020) NETL collaboration awarded funding to advance REES extraction technology, <https://netl.doe.gov/node/9840>
- Pan J, Zhou C, Liu C, Tang M, Cao S, Hu T, Ji W, Luo Y, Wen M, Zhang N (2018) Modes of occurrence of Rare Earth elements in coal fly Ash: a Case Study. *Energy Fuels* 32:9738–9743
- Scott C, Kolker A (2019) Rare Earth elements in coal and coal fly Ash. USGS Fact Sheet 2019–3048:4
- Stuckman MY, Lopano C, Hedin BC, Howard BH, Granite E (2019) Characterization and recovery of rare earth elements from Powder River Basin coal ash. 2019 International Pittsburgh Coal Conference. Pittsburgh, PA: University of Pittsburgh, Swanson School of Engineering
- Taggart RK, Hower JC, Dwyer GS, Hsu-Kim H (2016) Trends in the Rare Earth element content of US-Based coal Combustion fly ashes. *Environ Sci Technol* 50:5919–5926
- US DOE (2020) Rare Earth Elements 101. Infographic, U S Dept. of Energy, <https://www.energy.gov/sites/prod/files/2020/02/f71/Rare%20Earth%20Elements%20Infographic.pdf>
- US DOE, (2021) Carbon Ore, Rare Earth and Critical Minerals (CORE-CM) Initiative for U.S. Basins. Dept. of Energy National Energy Technology Laboratory, Announcement Number DE-FOA-0002364, <https://netl.doe.gov/node/10130>
- Zielinski RA, Finkelman RB (1997) Radioactive Elements in Coal and Fly Ash: Abundance, Forms, and Environmental Significance U.S. Geol. Surv. Fact Sheet FS-163-97

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