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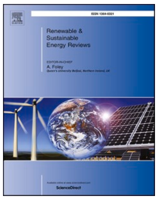

Rare earth element resource evaluation of coal byproducts: A case study from the Powder River Basin, Wyoming

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ABSTRACT

Domestic Rare Earth Element sources and production are limited in the United States and currently rely on final processing overseas. Increasing demand and resource security domestically has led to significant investigation into rare earth element domestic resources. Much of this work focuses on unconventional potential ore stocks, including coal and coal byproducts. This investigation focuses on coal byproducts generated as ash from coal burning power stations. Wyoming's Powder River Basin hosts the largest U.S. coal stocks for energy production, providing approximately 40% of all thermal coal mined in the U.S. In this effort, in section I, we have studied coal byproducts for rare earth element concentrations and compare these data to current alternative resource knowledge. We find that coal byproducts in this investigation are consistently high enough in rare earth element concentration (above the current Department of Energy 300 ppm cutoff grade) to warrant consideration as a promising potential resource. Rare earth element behavior within the host coal seams is also considered in an effort to better understand resource prospecting and ore body description. In Section II, we evaluate the economic feasibility of rare earth extraction from Powder River Basin coal byproducts using net present value analysis and the rare earth concentrations data from Section I. We calculate the break-even ash-to-oxide output and input unit costs for four coal stations in the Powder River Basin. All four stations have break-even unit costs that are higher than the mine-to-oxide operating cost reported for a traditional rare earth element mine. This is a promising result, especially given that it is more costly to refine rare earths from mined material than from ash. The results are highly sensitive to rare earth prices: given low long-term prices, none of the four stations can feasibly break even. Section III summarizes federal policy considerations in rare earth element resource development. The history of policy development, most recent focus on rare earth element specific funding legislation, paired with section I and II herein, suggest a robust opportunity for development of Wyoming based coal byproducts as a partial solution to current domestic rare earth element short falls and strategic needs.

1. Introduction

Rare Earth Elements (REE) are fundamental to modern technologies. Though they are strategically important resources, they are not rare *per se*. REE are not often found in typical trace metal ore deposits, and are limited to geologically uncommon deposits. The U.S. production of REE is limited with final processing taking place in China. Thus, new sources of domestic REE are attractive. Recently, research in the U.S. and

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Abbreviations: REE, rare earth elements; FA, fly ash.; BA, fly ash; PRB, Powder River Basin, WY; REO, rare earth oxide; HREE, heavy rare earth elements; MREE, middle rare earth elements; LREE, light rare earth elements; UCC, upper crustal component; DOE, U.S. Department of Energy; USGS, United States Geological Survey; REY, rare earth elements + yttrium; NETL, National Energy Technology Laboratory; NPV, net present value; USD, U.S. dollars; DPA, Defense Production Act; MMPA, mining and minerals policy act; NMPA, National Materials Policy Act; NMMA, National Materials and Minerals Policy, Research and Development Act.

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globally has focused on: (1) identifying unconventionally-sourced REEs in waste streams of industrial processes; and (2) developing new ways to enrich and extract these essential resources [1].

One promising strategy is to extract REE from waste products of coal combusted during electricity production [2]-called byproducts.[1] Large volumes of residual ash or fly ash (FA), and bottom ash (BA) offer potential for the recovery of REE and other trace metals. Solid combustion products of coal commonly have lower REE concentrations relative to many naturally occurring ore deposits. Still, processing coal byproducts offers several potential advantages over typical hard-rock mining and processing, including a long-term, high volume, and sustainable supply with environmental benefits associated by utilizing existing coal waste. Other benefits include:

1. The absence of capital costs associated with raw ore mining, including but not limited to necessary infrastructure, initial processing, transportation, environmental impacts, and reclamation.
2. Low-expense licensing and certification to permit REE extraction compared to conventional mining operations that can involve very high capital investment and associated risk assessments.
3. Availability of large volumes of current production and legacy coal byproducts, which are held in accessible industrial landfills.
4. The particle size of coal byproducts (specifically FA) is small (typically <500 μm with large relative surface areas [3], which facilitates simple chemical extraction.[2]
5. Avoiding radiogenic processing considerations such as removal of thorium and uranium.

The traditionally suggested economic cut-off grade of Rare Earth Oxides (REO) in these coal byproducts has been relatively high, and thus excluded many U.S. coals [4,5]. However, in addition to more recently considered REO concentrations [6–8], major element compositions and overall volume likely play equally dominate roles in coal based REE resource evaluation. More thorough assessment suggests extraction-favorable coal byproducts with acceptable REO concentrations may in fact be the best candidates as alternative REE stocks [9,10] and are more viable than high REO coal byproducts with costly extraction chemistry [11].

A combined assessment approach is used here to evaluate the coal byproducts of the Powder River Basin (PRB), Wyoming (Fig. 1). For ease of review of this combined approach, geologic, economic, and related policy analyses are divided into sections I, II, and III respectively.

2. Geological analysis

2.1. Introduction

Recent efforts to characterize coal and coal byproducts for use as new, non-traditional REE resources have largely focused on domestic coals with anomalously enriched (coal-relative) concentrations (e.g. Ref. [12]). Though REE enrichment is an important variable for determining resource potential, as a standalone variable it is limited: it ignores the volume and current usage practices of the coal, the potential for feasible metal extractability relative to resource chemistry, and can mask the reliability of REE distribution across a full coal body depending on the thoroughness of sampling. Furthermore, the foundational objective of assessing non-traditional REE resources is to secure new, reliable, long-term domestic sources. This would be best met by developing a low heterogeneity, high-volume, widely distributed domestic coal material from which REE could be extracted at low cost and energy inputs. One of the best sources to potentially meet all the aforementioned constraints are coal materials located at coal-fired power stations that are utilizing Powder River Basin (PRB) coal stocks. "Wyoming holds more than one-third of U.S. recoverable coal reserves at producing mines. The state has led the nation in coal production since 1986, and accounts for two-fifths of all coal mined in the United States. However, Wyoming's coal production has declined as U.S. coal-fired power plants have shut down and natural gas-fired and renewable-sourced electricity generation have increased." [13]. Previous geochemical assessments of PRB coal samples and coal byproducts are relatively limited, and could be generally described as "grab samples" [14,15]. This study provides the most detailed geochemical assessment of PRB coal byproducts to-date.

Calcium-enriched PRB coals constitute the largest percentage of current U.S. coal stocks, and are shown to be conducive to high recovery REE extraction [9,10].

REE patterns from PRB coal byproducts exhibit middle and heavy REE (MREE and HREE respectively) enriched profiles when normalized to the Upper Crustal Composition (UCC) [16]. REO values are in the 400 ppm range and, though traditionally low, are robust enough under current DOE guidelines (e.g. Refs. [8,17]) to be considered an alternative REE resource especially when extraction rates and overall material volumes are considered. Current production of REE is skewed towards more abundant light REE (LREE), which could lead to greater market demand for HREE in the years ahead given that HREE are used preferentially in end-use applications such as permanent magnets and renewable energy technologies such as wind turbines and solar panels.

This study shows in section 2.3 that the REE resources in PRB coal byproducts are relatively consistent in range of chemical variances that they are predictable enough for estimating resource potential on the basis of annual use or making reliable landfill estimates of older materials. USGS coal data [14] paired with knowledge of mining practices and resulting coal byproduct chemistry, however, suggests some natural variability in the trace element geochemistry of PRB coal; we suggest this indicates enriched zones, identified in transitional or high ash zones, similar to other studies [18–20] that are partially blended in some thermal coal products, or not shipped to power stations.

Understanding depositional and diagenetic history of a coal basin is required to best prospect for these concentrated zones. With coal chemistry in mind, we suggest prospecting for the highest REE concentrations and optimum extraction chemical behavior, while still maintaining coal chemistry requirements for fuel use. Based upon findings from this study, we suggest a balanced and dual-use coal can be utilized that benefits both end goals of coal-power generation and alternative resource development.

2.2. Methods and analysis

2.2.1. Sample collection

Samples were collected ($n = 117$) at four coal-fired power stations in the PRB (Stations 1, 2, 3 and 4 in Section II) over varying time periods. All power stations burn Tertiary PRB coal. Variability in individual station burner, cooling, and processing technologies results in different categories of coal byproducts collected per station. Fly ash (FA) and bottom ash (BA) of similar genesis were available at all stations, though landfill ash was only available at some stations and varies in character due to on-site operating procedures. For example, one coal station stores FA and BA in separate parts of its landfills, whereas another combines both ash types in landfill storage.

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[1] An additional consideration, is the fact that some coals can have naturally high concentrations of critical or high value REE [6]. The geochemistry of coal deposits depends on both the depositional environment and diagenetic history of a coal (e.g., basin fluid chemistry and migration, over and under burden chemistry/lithologies, etc.).

[2] It is also well documented that the smaller grain ash portion often contains higher concentrations of trace minerals [21,38,39], with little or no mechanical pre-treatment required. The impermeable holding ponds at coal-powered industrial sites contain coal combustion solid waste products in contact with water that could be easily adaptable to REE leaching/processing.

Fig. 1. Location of the Powder River Basin. This investigation focuses upon coal byproduct materials which were sourced from locations in the Wyoming portion of the Powder River Basin.

2.2.2. Sample analysis

All samples of coal byproducts were analyzed for major, minor, and trace elements (https://doi.org/10.17632/2znvfsdj3c.3) by ALS Geochemistry (Reno, NV). Individual samples were identified for additional evaluation by X-Ray Diffraction (XRD) and Scanning Electron Microscope (SEM) methods (conducted at both the University of Wyoming and Idaho National Laboratory-Center for Advanced Energy Studies).

2.2.3. Data comparisons

To be consistent with other investigations (e.g. Refs. [21,22]), the geochemical character of PRB coal byproducts were compared with worldwide samples using classification schemes described in Refs. [5,23]. The UCC normalization of [16] is used since it averages the composition of the upper crust of the Earth where traditional REE resources are found [5]. REE analyzed for resource evaluation are grouped with additional elements (e.g. scandium (Sc) and yttrium (Y)) that behave similarly to REE, and are thus used as prospecting elements in describing possible REE resources. “REY” is used to signify this group of elements. Geochemical investigation of samples in this study includes Y in all samples and Sc in only a few because of analytical procedures not quantifying Sc in certain samples. Comparison values used in this

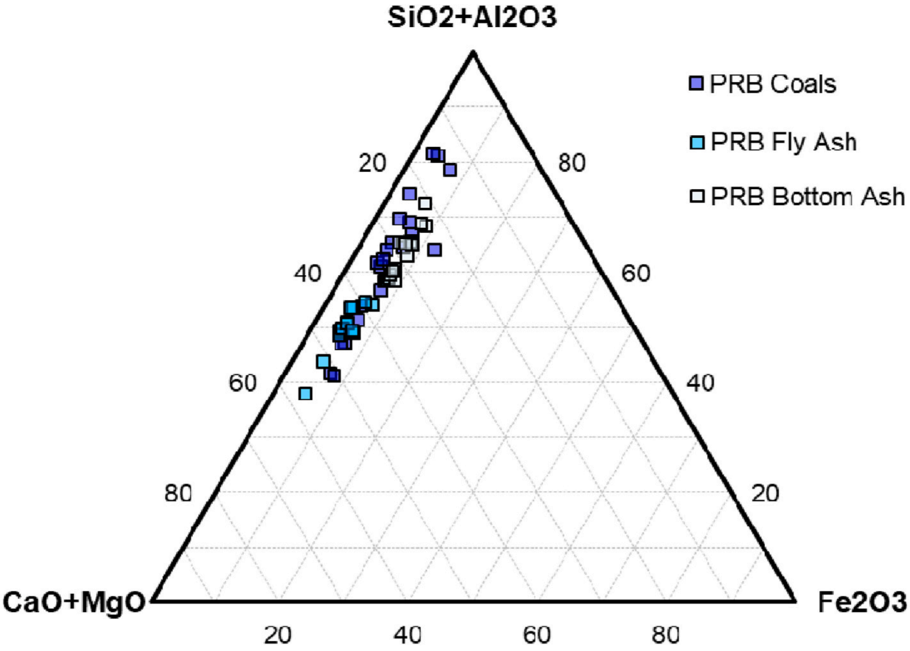

Fig. 2. Major oxide classification of PRB derived coal and coal byproducts. Byproducts of FA and BA tend to be calsialic.

investigation are REY averages in coal byproducts of 404 ppm globally and 517 ppm for U.S. samples [5]. However, both U.S. and global averages may be inflated to some degree because of attention given to select coal bodies which are favored due to increased critical element and REE concentrations, and not relative volume.

2.3. Observations and discussion

All samples described from the PRB are calsialic, being enriched in calcium oxide (CaO) relative to silicon dioxide (SiO_2), and have ferric oxide (Fe_2O_3) contents below 10 wt % (Fig. 2). Compositionally, PRB samples have relatively homogenous major and minor element concentrations, and trace element (including REE) behaviors, resulting in a distinct geochemical signature.

The compositional homogeneity, recorded from different locations over time, suggests that accurate basin-scale REE assessments of PRB coal byproducts can be developed reliably. REE behaviors are similar across all PRB samples, averaging 317 ppm REY. REE enrichment patterns are most similar to M-Type, group 3 profiles [5] when normalized to the UCC (Fig. 3).

M-Type REE distributions are characterized by a relative enrichment of MREE above both LREE and HREE [5], although in PRB samples here, HREE are also concentrated relative to LREE. M-type REE patterns have been suggested to pertain to: (1) circulation of acidic basin waters, possibly on a basin-wide scale, where high REY concentrations increase in coal by scouring/leaching of other minerals followed by deposition within coal seams under reducing conditions [5]; (2) higher sorption of MREE and some HREE on the humic matter [24] and/or clay minerals [6] which may include basin-wide scouring sources; and, (3) input from proximal REE-deposits, such as the Bear Lodge carbonatite located along the northeastern margin of the PRB [25]. A basin-wide scouring model with sorption by humic and clay minerals for the enrichment of PRB samples seems most reasonable as all samples, even those from differing coal seams [26] and those further removed from Bear Lodge deposits, exhibit similar UCC-normalized REE-profiles [27].

There are several locations where REE most likely concentrate within PRB coal seams. An abundance of organic sulfur and humic material is noted in major PRB coal seams [28,29], as is volcanogenic material from air-fall ash [30], and clay [6].

Two distinct tonsteins have been identified in northern PRB coals which are utilized as thermal coal [30]. Recent work [30] confirms these tonsteins and additional presence of non-volcanogenic REE bearing horizons. Rather than single process REE enrichment, PRB coal seams are enriched by multiple sources (volcanogenic input, and basin wide scouring & contribution in clays).

This multi-source REE contribution in M − and H-type REE coals is described elsewhere [31]. Clay speciation associated with coal seams appears to be fundamental in terms of REE-load potential; those with more ion-exchangeable clays tend to be higher in REE concentration [6]. Indeed, recent work on coal specific REE behavior has shown both contribution of REE from tonsteins and clay in PRB coals, though in separate portions of the same seams [27].

For PRB samples evaluated here, relative abundance and distribution of REE-individual species are observed with a slight dominance of MREE over HREE occurring in both ash types, and BA tends to have higher total REE concentration (Fig. 4). The increase in REE concentrations in BA can be explained by the abundance of slag collecting in the BA quantity of the byproduct. Slag can exist internal to the burner for several weeks, providing extended exposure times for REE-bearing vapor and condensation.

2.3.1. REY, REO, critical REY%, and Outlook Coefficient of REY

Average REY values of 317 ppm in PRB coal byproducts may be lower than the global and U.S. averages because of overall lower concentrations in Wyoming coals, or because of efficient mining practices which are not harvesting the richest zones of REE in bearing coals (i.e. higher ash coals). We show that PRB coal byproducts are generally consistent basin-wide, reflecting the occurrence of a widespread coal sediment system that is laterally consistent over a large extent of the basin [26]. That is to say, coals used in power stations that produce materials evaluated herein reflect a historical depositional system as a mostly homogenous coal bog [29]. However, there is evidence that portions of the PRB coals are REE-enriched in places. An explanation is favored by comparisons to USGS coal data [14] for Wyoming coals which show higher REE concentrations in some PRB samples when scaled to byproduct REE concentrations measured in this investigation. And again, recent analysis of PRB coal core strongly supports this conclusion [27], where REE-enriched bounding layers are described in PRB coals. Another example is a range of REY concentrations measured from a single power station sourcing more variably mined coals; indeed, coal-fired power plants typically combust blends of coals for a variety of performance and related reasons. Values as high as 458 ppm and as low as 250 ppm from a single FA landfill location confirm coal and coal partings input is variable.

REO is a common designation of REE species for economic assessment, accounting for the distribution of REE as oxides. In historical REE markets (those prior to current U.S. strategic needs) economic cut-off grade for coal byproducts was considered to be 1000 ppm REO of total REE in a given coal byproduct [4]. More recent markets (circa pre-2016) suggested an economic cut-off grade around 800 ppm REO of total REE [5], while current DOE coal based REE assessments are set at 300 ppm [32]. This value is specific to extraction feedstock concentrations. PRB coal byproducts from this investigation, on average have REO values of 383.7 ppm.

In addition to total REO evaluation, specific REE species must be evaluated by the proportion of resource that is critical (of most value). High total concentrations of REE or REY do not necessarily produce the highest yields of the most economically important elements. Commonly, high concentration total REE resources are inundated with low or negative value, non-critical REE species. Since critical REE elements are of greater value, they are considered here as a percentage of the total REE resource in evaluating ore stock quality. Coal ash byproducts with critical REE concentrations greater than 30% are considered “promising” as a REE resource, and above 50% as “highly promising” [5]. In the northern PRB, consistent values above 36.5% occur in coal byproducts, showing PRB samples have concentrations that merit further investigation.

Outlook Coefficient of REY (C_{outl}) is a method used to evaluate an REE ore stock grade. C_{outl} (or K_{outl}) is an index proposed by Ref. [33] to evaluate the ideal composition of a REE stock in terms of market trends by comparison of critical vs. excessive REE in stock [5]. As market trends potentially alter REE resource needs, the C_{outl} may be adjusted to better reflect economic adjustments. For this investigation, the critical REE considered are Nd, Eu, Tb, Dy, Er, and Y, with excessive REE including Ce, Ho, Tm, Yb, and Lu. The evaluation is $C_{outl} = (Nd + Eu + Tb + Dy + Er + Y/\Sigma REY)/(Ce + Ho + Tm + Yb + Lu/\Sigma REY)$. A C_{outl} value greater than 0.7 is considered a “promising” REE resource, with values greater than 3.1 considered “highly promising” [5]. Samples from the PRB average $C_{outl} = 1.01$.

In consideration of both critical % REY and the Outlook Coefficient of REY, all PRB coal byproducts in this investigation fall within the “promising” REE resource field. Of particular interest are those from the northern PRB where overall REO content, critical REE %, and C_{outl} are highest (Fig. 5). Again, additional consideration of feed coal sources and the possibility of increased REE concentrations in specific zones may further increase the value of potential resources noted here.

For coal byproducts to be evaluated as potential REE resources, individual REE species (i.e. critical REE %), major element geochemistry related to the reactivity and extraction of REE, and overall volumes of byproduct must be considered in unison. Economic feasibility directly relates to these variables, which are often ignored in place of total REE concentration.

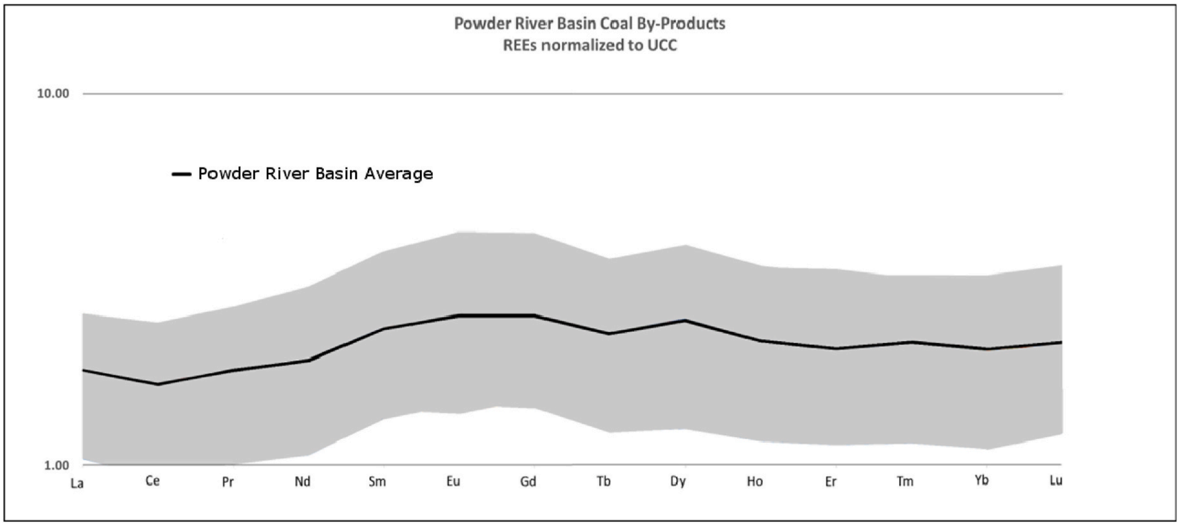

Fig. 3. Upper Crustal Composition normalized REE profile for all coal byproducts evaluated in this investigation. The profile fits an M-Type, group 3 profile [5].

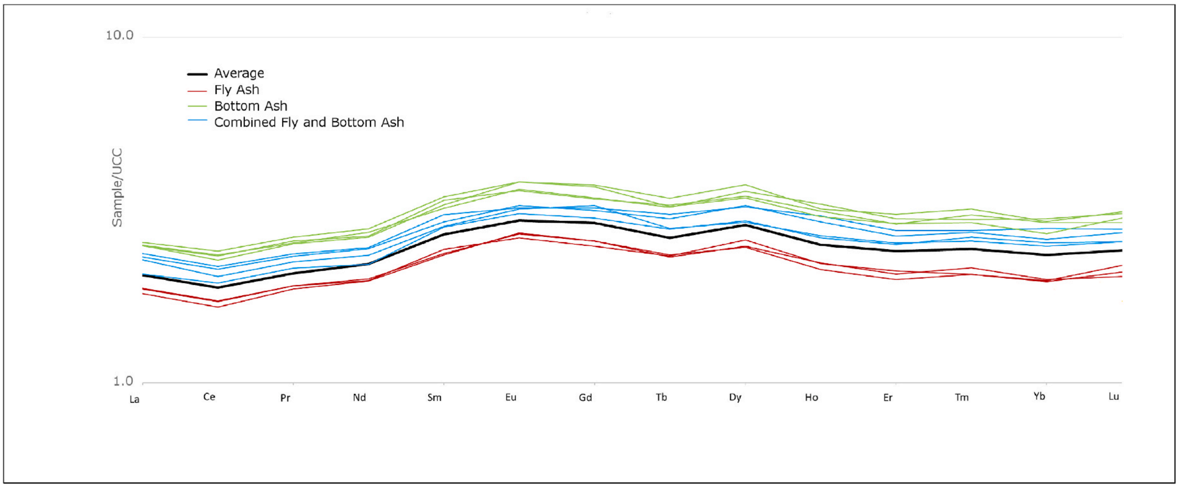

Fig. 4. UCC normalized profiles of PRB derived coal byproducts. This example shows coal byproducts collected at a single power station (Station 3), but is indicative of all samples included in this work. Bottom Ash material is more enriched in total REE across all REE species when compared with Fly Ash. However, the profile is similar between all ash types.

Major element geochemistry of coal and coal byproducts is vastly important when extraction of REE is being evaluated. Past studies of coal and coal byproducts from the PRB and other U.S. sources [18,19] show that silica (Si) and calcium (C) content plays a dominant role in REE extraction success [9,10].

Coal byproducts (specifically FA) [9] exhibit drastically different extraction percentages between Si-enriched and Ca-enriched coal byproducts using modern benchtop extraction methods. Appalachian basin coals contain the highest REE-concentrations in the U.S. (591 ± 91 ppm) but have almost no Ca (less than 4 wt % CaO), and a median REE extraction rate of only 29.6%. In contrast, PRB coals enriched in Ca (around 25 wt % CaO) exhibited REE extraction rates of 70%. Despite having average REE-concentrations of only 337 ± 69 ppm, a PRB ash would produce approximately 235.9 ppm in extracted solution (~36% of which is critical REE), while a superficially attractive Appalachian basin ash would produce only 174.94 ppm in extracted solution (~38% of which is critical REE) (Fig. 6). In support of these findings, recent NETL extraction experiments have yielded promising results from PRB Ca-enriched fly ashes [10]. These examples shows how a comprehensive geochemical approach is required for properly nuancing REE resource evaluations and avoiding traditional processing pitfalls when commercializing an alternative REE resource.

REE in coals occur in various minerals, grain coatings, and organic constituents which affect extractability. The majority of REE in PRB coals likely occur in clay species concurring with descriptions of coals [27] and clays [6], though REE-bearing tonsteins and detrital primary mineral phases within PRB coals [33] are also present. Tonstein and detrital REE bearing minerals within coals are often resistant to burner processes [33], and in those cases the resulting ash product is often less enriched in volatiles (trace elements) making ash-tailored extraction processes less effective. Better understanding refractory behavior of PRB materials will help guide extraction work in the future.

REE-enrichment can vary across an individual coal bed due to differences in clay, organic matter, and volcanogenic or detrital minerals [21,34,35]. In PRB coals the highest total REE concentrations associated with coals are located in bounding layers [27]. These clay-rich zones ("partings") are commonly by-passed by mining operations in an effort to remove purer thermal coal and minimizing ash production. With minimal research into these potential REE sinks, a new strategy to mine PRB coals with slightly increased ash content yet a significant increase in REE resources may be possible. Chemical influences affecting coal as both a fuel source and potential alternative trace metal resource must be

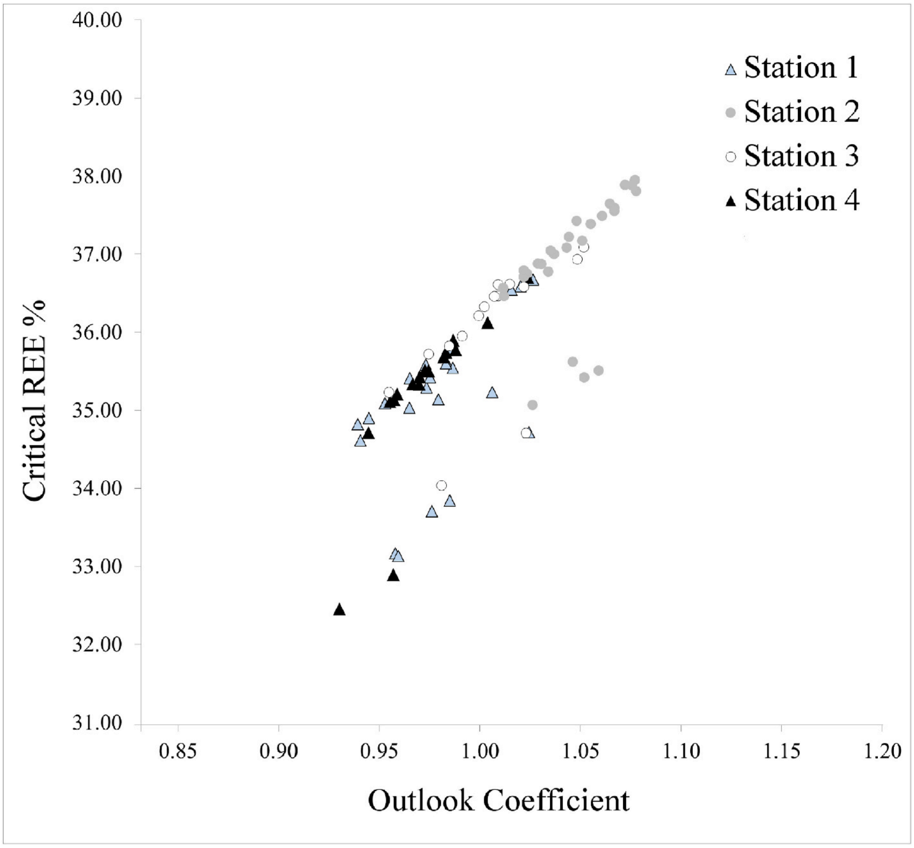

Fig. 5. Outlook Coefficient compared to Critical REE percent in PRB derived samples from this investigation. In comparison to Ref. [5], PRB samples group within the "promising" field for REE resource consideration.

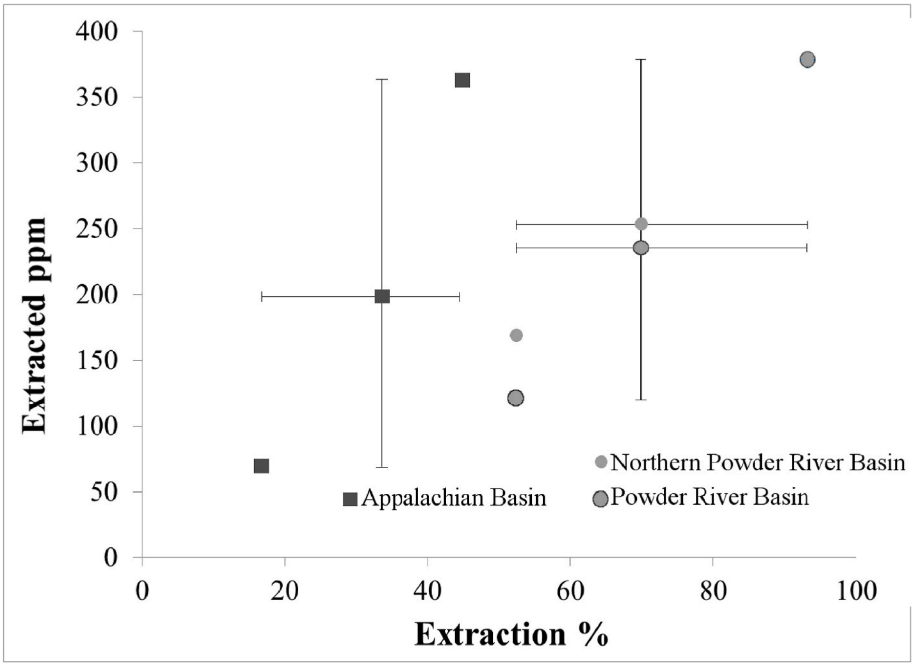

Fig. 6. Extraction Percent compared to Extracted ppm (total) of Appalachian Basin derived fly ash and PRB derived fly ash. This comparison utilizes values supplied in Taggart et al. (2016) [8], and samples from this investigation (i.e. Northern Powder River Basin).

understood to benefit both metals extraction a fuel use.

Further development of efficient extraction processes, continued increases in demand, and U.S. strategic benefits currently lowering the cut-off grade of coal byproducts to 300 ppm REY, make PRB coal byproducts attractive for more resource investigations. Research and development of REE extraction from coal byproducts is strongly suggested, not just by this investigation, but other notable studies (current NETL research for example), and may very well put coal byproducts well within economic reach as a REE resource sooner than later. Much of the extraction research needed is scale-up to larger than bench-scale methods [9,36] that are already proven [10].

We suggest REE enriched coals and related bounding layers could be prioritized for use in power stations when REE are in high demand if those prioritized fuel sources do not interfere with overall power production. Complex coal petrography evaluation paired with geochemical behavior related to fuel quality is already benefiting some coal regions [37]. Strategic REE enriched stocks could also be placed in reserve for later use. The volume and distribution of PRB coal byproducts makes it a valuable target for developing extraction techniques, as PRB coals make up the largest single coal stock in the United States. The existing coal byproducts from decades of PRB consumption may in fact already represent a significant REE strategic resource in the United States. Regardless of a resource being considered as promising, policy and related regional infrastructure must become part of the overall assessment.

3. Economic analysis

In this section, economic and geological data are combined in a net present value (NPV) analysis of rare earth oxide (REO) extraction from coal ash generated at Powder River Basin (PRB) coal stations. The analysis focuses exclusively on hypothetical rare earth operations, established to convert coal ash from the existing coal stations into rare earths.[3] The baseline results, which are presented in Section 3.1, indicate that extracting REOs from PRB coal ash is a potentially feasible method of establishing domestic rare earth production, depending on the market prices of rare earths. In Section 3.2, additional sensitivity analysis is conducted to observe how changes in key parameters (e.g., years of operation, proportion of rare earth product sold) influence the results. Section 3.3 concludes.

3.1. Baseline net present value analysis

NPV analysis evaluates the feasibility of a project and captures the opportunity cost of investing in that project some number of years, *n*, into the future. Funding for the project could instead be invested in an alternate investment, which would earn interest at the discount rate, *r*. NPV analysis for the four PRB coal stations (indexed by $i = 1, 2, 3, 4$) is based on each station's initial fixed cost, FC_i, and each station's annual profit (the net of revenue in year *t*, $R_{i,t}$, over variable costs, $VC_{i,t}$). The NPV equation for a given station is

$$NPV_i = -FC_i + \left(\frac{1-\rho^{n+1}}{1-\rho}\right)\left(R_{i,t} - VC_{i,t}\right),$$

in which ρ is the discount factor: $\rho = 1/(1+r)$. All baseline parameter values used in the net present value analysis are shown in Table 1. The table also shows ranges of the parameters used in the subsequent sensitivity analysis.

Table 1

Baseline parameter values (in bold) and ranges used in the net present value analysis and sensitivity analysis.

Parameter	Baseline	Feasible Range
Days operated per year	310	[275, **310**, 345][a]
Years of operation (*n*)	12	[6, **12**, 18][b]
Discount rate (*r*)	0.07	[0.03, 0.05, **0.07**][c]
Proportion of total product sold	1.00	[0.50, 0.75, **1.00**][d]
Ash yield	0.70	[0.53, **0.70**, 0.88][e]
Fixed cost in millions of USD (FC_i)	1	[5, **15**, 25][f]

[a] The baseline number of days operated per year, 310 days, is set assuming that U.S. coal-fired stations are unavailable about 15% of each year [40]. The lower bound (275) was constructed by taking one of the station's reported average annual fly ash production (in tons/year) and dividing it by the same station's reported average daily fly ash production (in tons/day); the result was 275 (in units of days/year). The upper bound was then constructed such that the number of days between the baseline and the upper bound was identical to the number of days between the baseline and the lower bound (310–275 = 35 days).

[b] PacifiCorp plans to retire its Wyoming coal-fired power plants by 2039. One of the two PRB coal stations has an expected closing date of 2027 (six years from now) and another has an expected closing date of 2039 (eighteen years from now) [41]. Six and eighteen years are thus used as the lower and upper bounds, respectively. The average of the two (12 years) is used as the baseline.

[c] On an annual basis, the Office of Management and Budget (OMB) specifies appropriate discount rates to be used in cost-effectiveness analyses of federal programs [42]. The OMB recommends using 7% as the real discount rate for regulatory analyses and public investment conducted in 2021, so 7% is set as the baseline. However, the OMB recommends submitting two estimates: one with a discount rate of 7% and one with a discount rate of 3% [43]. 3% is thus set as the lower bound. For the middle bound, the average of 3% and 7% (i.e., 5%) is used.

[d] Given factors such as quickly rising demand for rare earths and current lack of domestic rare earth production [44], the baseline assumes that all the output from the domestic rare earth operations would be sold. As a lower bound, it is assumed that only half of the product would be sold; for example, advances in electrodeposition could reduce the need to mine new rare earths [44]. For the middle bound, the average of 0.5 and 1 (i.e., 0.75) is used.

[e] PRB ashes, which are notable for having high extractable rare earth element (REE) content, yield 70% of total REE through heated nitric acid digestion [9]. 0.70 is thus used as the baseline ash yield. The lower and upper bounds are set as a 25% reduction and a 25% increase in the baseline, respectively.

[f] The fixed cost variable is different from the others in that it is a calibrated parameter. The analysis yields every station's maximum fixed cost in the absence of annual variable costs. Sensitivity analysis shows the effect of fixed cost on net present value over a wide range of possible fixed costs; this builds in the flexibility to consider a wide range of construction technologies and costs.

Coal ash produced at a station represents a "flow," in that ash is continually produced as a station operates. The economic data includes estimates of the average volume of coal ash produced at each coal station (in US tons), both in terms of fly ash (FA) and bottom ash (BA).[4] Although rare earths can be refined from both FA and BA, this analysis considers only FA because of its volume and relative ease of processing.[5] The average volume of FA produced per day at a station is multiplied by the number of days that a station operates per year for an estimate of the annual volume of FA produced at a station. Prior research indicates that U.S. coal stations are unavailable about 15% of the time [40]. For each station, the baseline number of days operated per year is set at 310, which represents 85% of the total days in a calendar year.

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[3] The analysis ignores any value from the coal stations not associated with rare earths (e.g., value from generating electricity).

[4] The estimates are grounded in each station's total coal input (in tons/day). Minimum total ash output is 5% of coal input while maximum total ash ouput is 12% of coal input. Each PRB station reported the proportion of total ash output that is BA versus FA (e.g., 80% FA, 20% BA). Those proportions are used to calculate the BA and FA produced (in tons/day), both for minimum and maximum total ash output. The averages are then calculated and used in this analysis.

[5] Refining BA would require crushing and grinding in addition to the extraction steps used for FA, and the extra costs associated with the additional processing could make the process of refining rare earths economically infeasible. Nevertheless, the authors replicated all calculations in this section using combined BA and FA; the results are available upon request.

In addition to the flow of coal ash that is continuously generated, each station also has existing landfill ash (e.g., in ash ponds). This represents an existing “stock” of ash. It is assumed that each station would refine a constant amount of landfill FA each year such that the entire stock of landfill FA has been refined by the coal station’s final year of operation. The total amount of ash available for refining rare earths in any given year is thus the sum of the new FA generated that year plus the portion of landfill FA available for refining in that year.

The geological data consists of average rare earth element (REE) concentrations, in parts per million (ppm), in the ash at the four coal stations. This allows for calculating expected rare earth quantities given ash quantities. It is assumed that each station would refine its entire annual volume of FA into rare earths (i.e., no FA would be used for other products such as concrete). The ppm concentrations are reported in FA, BA, landfill FA, landfill BA, and combined landfill FA and BA.[6] The ppm concentrations are converted to percent concentrations by dividing by 10,000. Each percent concentration is converted to a proportion (out of one) and then multiplied by the total amount of FA and LFA refined per year for an estimate of the quantity of each REE produced per year (in US tons per year). In a consecutive calculation, the volumes of REE refined are converted to volumes of REOs refined (in US tons per year) using element to oxide conversion factors. These conversions are utilized because there are generally better price estimates for REOs than REEs. An underlying assumption in the NPV analysis is that all rare earths are sold as REOs.

To calculate total annual revenue at every station, the volumes of REOs refined per year are first multiplied by the average prices of those REOs. For the majority of REOs, the average price is taken as the average monthly price during the 5-year duration from August 2016 to August 2021, as found from Asia Metals Inc., from Bloomberg. com [45]. Five-year average prices for Gd, Sc, and Yb are constructed using the USGS Minerals Yearbooks [46].[7] Second, the volumes are multiplied by the proportion of total product sold. Given factors such as quickly rising demand for rare earths (e.g., from increased use of electronic devices and green technologies) and current lack of domestic rare earth production, it is assumed that 100% of the total REO product would be sold. Third, the volumes are multiplied by the ash yield. There will naturally be inefficiencies in the process of converting coal ash to REOs, and the ash yield captures those inefficiencies. The NPV analysis incorporates an ash yield of 0.7, as estimated for REE in the PRB [9]. The process of refining from ash to REOs is more efficient than the process of refining from ash to REE, so the 0.7 value likely underestimates the revenue at each coal station. Fourth, for every station, the above products are summed across all non-excessive REOs. Excessive rare earths, which include Ce, Ho, Tm, and Lu, are ignored; these rare earths tend to have low market value because of overabundance and less usefulness in current technology trends. Total annual revenue for each station, which is assumed to be constant every year of operation, is shown in Fig. 7.[8] The first set of bars show potential annual revenue given average prices. The second and third set of bars show potential annual revenue given low and high prices, which are set at 0.5 and 1.5 times average prices, respectively.

There is existing literature on the economic feasibility of rare earth production (e.g. Ref. [47]), but the costs associated with rare earth extraction from coal ash in the PRB appear mostly undocumented. The maximum feasible fixed cost for each coal station, FC_i^{max}, is thus calculated using break-even NPV analysis that incorporates each station’s potential annual revenue in the absence of annual variable costs. Setting the NPV equation equal to zero and substituting in $VC_{i,t} = 0$ yields

$$FC_i^{max} = \left(\frac{1-\rho^{n+1}}{1-\rho}\right)R_{it}.$$

Each station’s maximum fixed cost is shown in Fig. 8. As expected, the maximum fixed cost for each station is lowest when considering low market prices of REOs over the duration of the rare earth operation and highest when considering high market prices over the duration. Station 1, which produces the most ash, has the highest maximum fixed cost. The opposite is true for Station 3, which produces the least ash. The baseline fixed cost is centrally set at 15 million USD; this leads to positive NPV under some combinations of parameters and negative NPV under others.

Annual variable costs are given by

$$VC_{it} = Q_{it}^k w^k,$$

in which Q is volume and w is the unit cost. The superscript, k, allows for two alternate specifications of the unit cost. The first specification, denoted by $k{=}REO$, represents an output unit cost that is calculated with the volume in terms of total amount of REOs produced. The second specification, denoted by $k{=}ash$, represents an ash-to-oxide input unit cost that is calculated with the volume in terms of total ash refined. Break-even NPV analysis is used to determine the maximum feasible output and input unit costs for each coal station, with the fixed cost set at the baseline. Setting the NPV equation equal to zero and solving for w^k yields

$$w^k = \frac{R_{it} - \frac{FC_i}{\left(\frac{1-\rho^{n+1}}{1-\rho}\right)}}{Q_{it}^k}.$$

The break-even output and input unit costs, given average, low, and high prices, are shown in Figs. 9 and 10, respectively. Higher break-even unit costs are more promising: the higher the break-even unit cost for a station, the higher the variable cost that a station can absorb and still break even (in terms of NPV). Negative unit costs imply that a station could not break even with all parameters set at their baseline values. The SRK Molycorp report reports a mine-to-oxide operating cost of 1.17 USD per pound of total REO [48]. Refining from mined material to REO is likely more costly than refining from ash to REO, because ash is already partly refined [47]. For this reason, the 1.17 USD value is expected to be an overestimate of the cost of refining REOs from coal byproducts. If the actual output unit cost were 1.17 USD for PRB coal byproducts, Stations 1 and 4 would earn positive NPV given average and high market prices. Given low market prices, NPV would be negative for all stations besides Station 1.

To account for uncertainty in production costs, the NPV for each coal station is estimated over a wide range of output unit costs, with all parameters set at their baseline values (Table 1) and given average market prices over the entire duration of the operation. The results are shown in Fig. 10. Station 1 could earn positive NPV with output unit costs under $14 per pound of REO. Stations 2 and 3 could never earn positive NPV, even if output unit cost were zero. Station 4 could earn positive NPV with output unit costs under $4 per pound of REO.

Fig. 11 shows every station’s NPV over a range of possible output unit costs, given average, low, and high market prices. At low enough output unit costs (e.g., under $4 per pound of REO), Station 1 could earn positive NPV even with low market prices. Station 2 could only earn

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[6] For stations 1 and 2, there is geological data on REE concentrations (in ppm) in FA, BA, and LA. LFA concentrations are extrapolated using $LFA = \frac{FA}{FA+BA}\cdot LA$ while LBA concentrations are extrapolated using $LBA = \frac{BA}{FA+BA}\cdot LA$. For station 3, there is data on REE concentrations in FA, BA, LFA, and LBA. For station 4, there is only data on REE concentrations in FA and BA, so it is assumed that $LFA = FA$ and $LBA = BA$.

[7] The most recently available five-year period is used: 2014–2018 for Gd and Sc, 2007–2011 for Yb.

[8] Constant potential annual revenue is a strong assumption, because there will be potentially large variation in the price and demand of REs over time. However, using average prices in the analysis helps capture some of the potential variation. Further, all key results in this section are shown over average, low, and high prices.

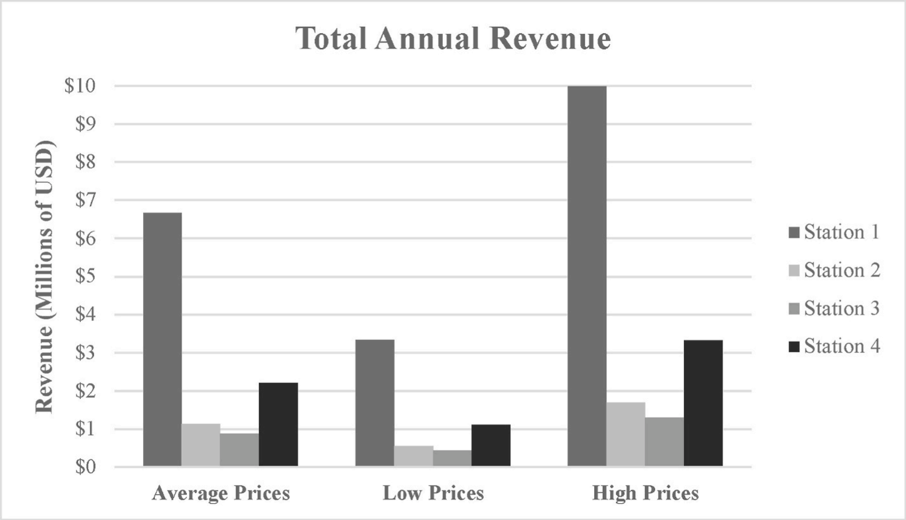

Fig. 7. Total annual revenue at each station given average, low, and high market prices of rare earth oxides.

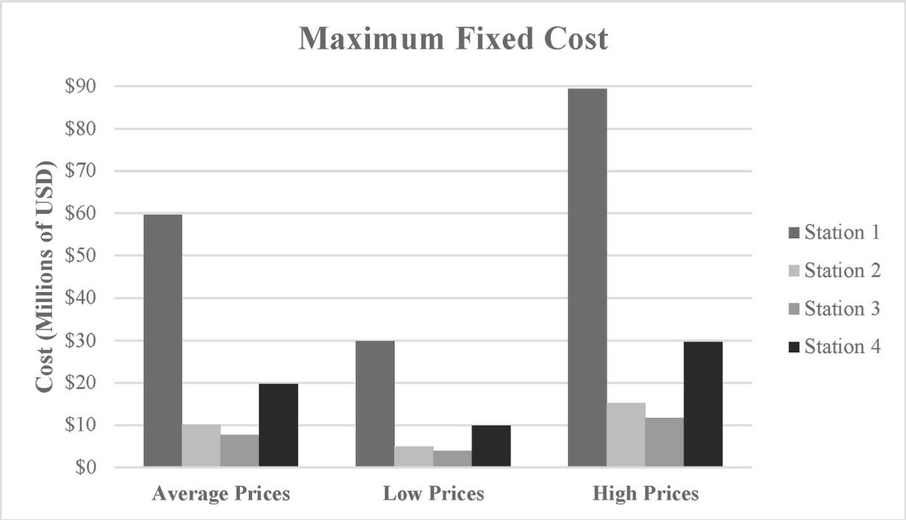

Fig. 8. Maximum fixed cost at each station, given average, low, and high market prices of rare earth oxides.

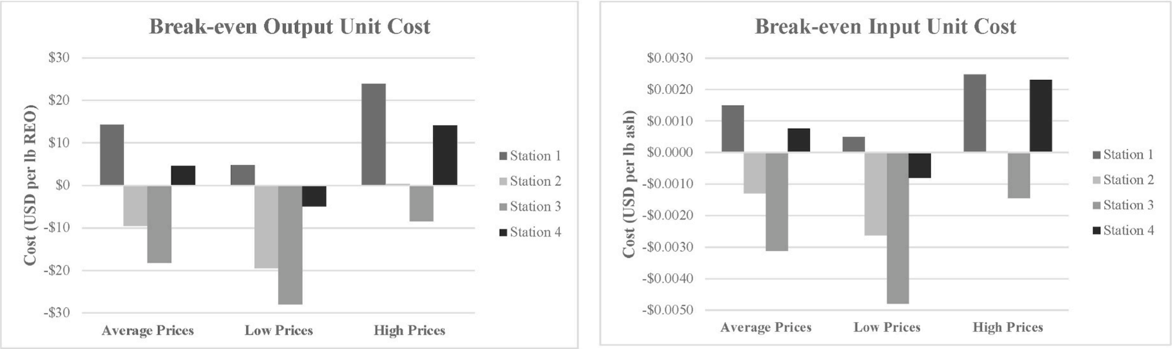

Fig. 9. Plot a (left) shows the break-even output unit costs (i.e., costs per pound of rare earth oxide produced) for every station given average, low, and high market prices of rare earth oxides. Plot b (right) shows the break-even input unit costs (i.e., costs per pound of ash refined) for every station given the same set of prices.

positive NPV given high market prices and low enough output unit costs (e.g., under $0.25). Station 3 could not earn positive NPV even given high market prices. Station 4 could earn positive NPV given high prices (if output unit costs were under $14) and given average prices (if output unit costs were under $4).

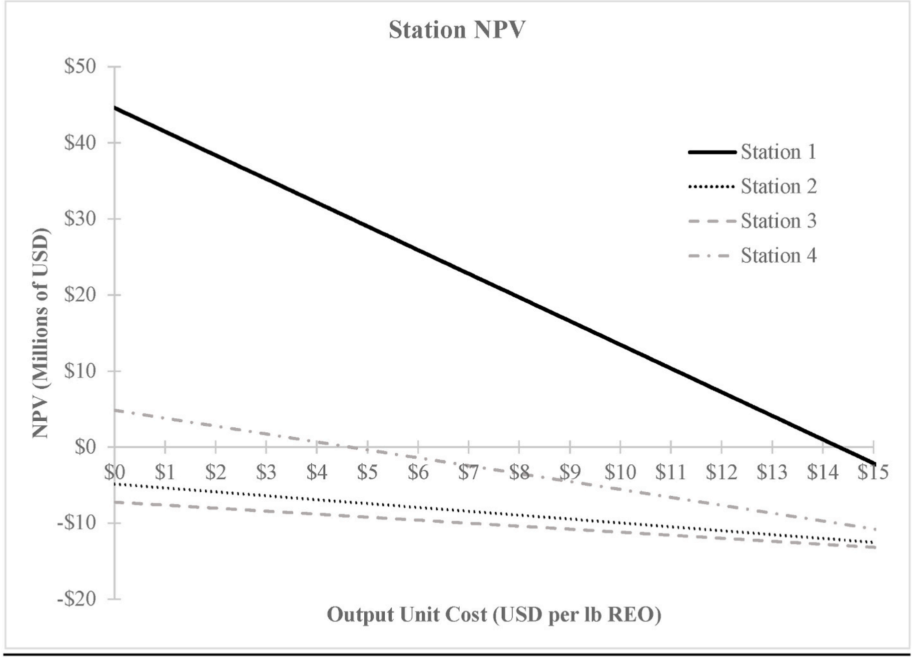

Fig. 10. Every station's NPV over a range of possible output unit costs, given average market prices of rare earth oxides.

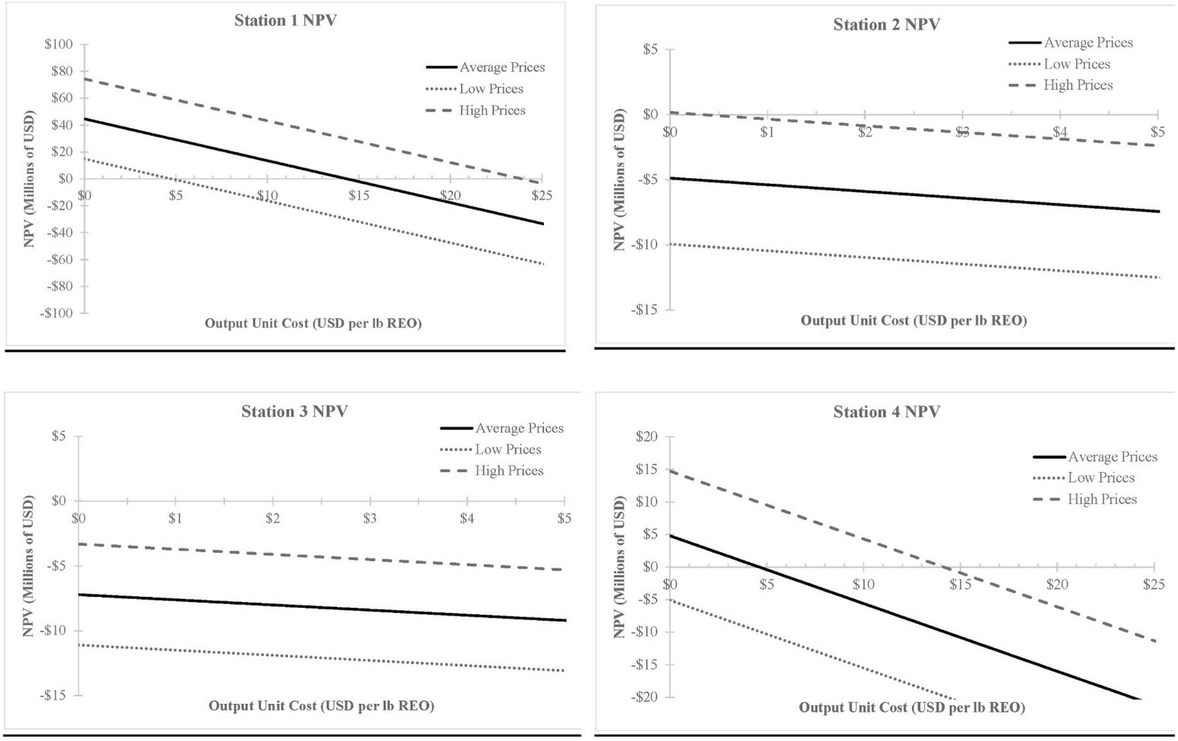

Fig. 11. Every station's NPV over a range of possible output unit costs, given average, low, and high market prices of rare earth oxides. Plots a (top left), b (top right), c (bottom left), and d (bottom right) represent Stations 1, 2, 3, and 4, respectively.

3.2. Sensitivity analysis

In this section, a sensitivity analysis is conducted over ranges of the parameters in Table 1. Fig. 12 displays the results, with one plot for each parameter of interest. All parameters (besides the parameter of interest) are held constant at their baseline values. As in Section 3.1, it is assumed that only FA is refined and that excessive rare earths are ignored. Average prices are used, and the output unit cost is set at $1.17 per pound of REO (i.e., at the SRK Molycorp estimate) [48]. Results are as expected. NPV increases with increases in days operated per year, ash yield, proportion of total product sold, and years of operation. NPV decreases with increases in fixed cost and the discount rate.

Briefly, the implications of changes in each parameter are discussed. For days operated per year, Station 1 is able to always earn a positive NPV even without generating because of the large existing stock of landfill at Station 1. It is not possible for Stations 2 and 3 to earn positive

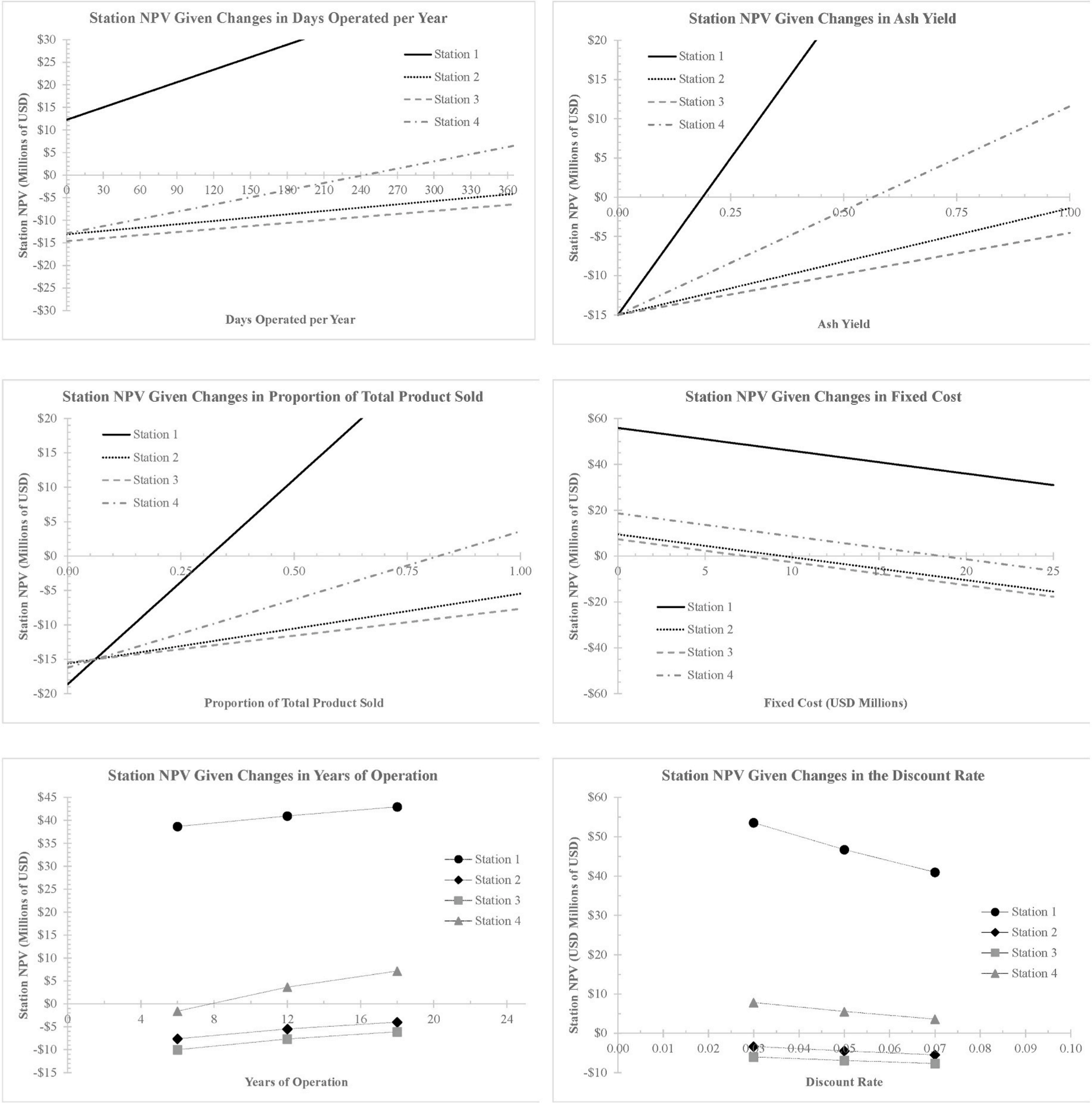

Fig. 12. Station NPV given changes in key parameters: days operated per year (plot a, top left), ash yield (plot b, top right), proportion of total product sold (plot c, center left), fixed cost (plot d, center right), years of operation (plot e, bottom left), and discount rate (plot f, bottom right). Slopes in the top four plots are linear while slopes in the bottom two plots are non-linear.

NPV, even if the coal stations operated every day of the year. Station 4 can earn positive NPV if operated for more than 240 days per year.

At a low enough ash yield (e.g., 0.15), every station would earn negative NPV. Station 1 would earn positive NPV at an ash yield above 0.20 while Station 4 would earn positive NPV at an ash yield above 0.60. Stations 2 and 3 would never earn positive NPV, regardless of the ash yield. At a low enough proportion of total product sold (e.g., 0.30), every station would earn negative NPV. Station 1 would earn positive NPV at a proportion sold above 0.35 while Station 4 would earn positive NPV at a proportion sold above 0.85. Stations 2 and 3 would never earn positive NPV, regardless of the ash yield. At a low enough fixed cost (e.g., under 6 million USD), the NPV of all stations would be positive. At a high enough fixed cost, the NPV of all stations would be negative.

The years of operation and discount rate parameters are different from the rest in that changes in the two parameters lead to non-linear changes in NPV. Over the feasible ranges of the two parameters (Table 1), Stations 3 and 4 could not earn positive NPV. Station 1 earns positive NPV over the entire feasible range of both parameters. Station 4 earns positive NPV over the entire feasible range of the discount rate, but it would earn negative NPV at the lower bound of years operated per year (6 years).

3.3. Discussion

This analysis yields insight into the feasibility of operations that would refine rare earths from existing and newly-generated ash at PRB coal stations. The costs of extracting rare earths from coal ash in the PRB are largely undocumented. The analysis yields the maximum fixed cost that each station could face, in the absence of variable costs, in order to at least break even in terms of NPV. Given a baseline fixed cost, the analysis also yields the output and input unit costs that would allow PRB coal stations to break even. If a station were to incur an actual unit cost lower than its break-even unit cost, then that station could operate at a positive NPV if a future refining operation were established. The results show that, over a range of parameters, and given average, low, and high REO market prices, there is the potential for some stations in the PRB to earn positive NPV from refining rare earths from coal ash.

Fixed costs have a significant impact on the feasibility of rare earth refining operations. To help fund fixed costs, coal stations could attempt to obtain state funding. Alternatively, stations could combine their rare earth operations, which would require the construction of only one refining facility. A higher fixed cost could be incurred if stations were to split the fixed cost of one refining facility. The decrease in fixed cost from a combined refining facility would have to be large enough for each station to be able to cover the costs required to transport their coal byproducts to the lone refining facility. It is possible that the refining facility could be located out of state. It is also possible that there may be facilities in different states for different stages of refined product. The PRB stations would therefore need to ensure that the annual revenue they obtain from selling their end product is high enough to justify the variable cost of producing that end product.

Some PRB coal stations have break-even unit costs that are higher than the SRK Molycorp mine-to-oxide operating cost of 1.17 USD per pound of TREO, which is promising because the ash-to-oxide operating cost would likely be lower than the mine-to-oxide operating cost (due to ash already being partly refined). If stations can absorb the mine-to-oxide operating cost and earn positive NPV, then those stations would earn even higher NPV when operating under the reduced ash-to-oxide operating cost. Once there are estimates of the unit costs for refining PRB coal ash, economies of scale will have to be considered. Operating costs could diminish as more rare earths are refined from ash, which would represent a situation of increasing returns to scale. Alternatively, the opposite could occur, and there could be decreasing returns to scale.

The results are highly sensitive to key variables, including fixed and variable costs, rare earth oxide prices, days operated per year, ash yield, proportion of total product sold, years of operation, and discount rate. Additional research, especially on the costs of technologies needed to refine rare earths from coal ash in the PRB, is needed to more accurately determine the feasibility of rare earth refining operations in the PRB.

4. Policy analysis

4.1. Federal executive branch developments

The current U.S. Administration has made domestically sourced REE's a national priority, including those derived from unconventional sources such as coal byproducts. On December 20, 2017, President Trump signed Executive Order 13,817 [49] setting forth "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals." The Executive Order sets forth the following policy:

> "It shall be the policy of the Federal Government to reduce the Nation's vulnerability to disruptions in the supply of critical minerals … The United States will further this policy for the benefit of the American people in a safe and environmentally responsible manner, by:
>
> "(a) identifying new sources of critical minerals;
>
> "(b) increasing activity at all levels of the supply chain, including exploration, mining, concentration, separation, alloying, recycling, and processing critical minerals;
>
> "(c) ensuring that our miners and producers have electronic access to the most advanced topographic, geologic, and geophysical data …. ; and
>
> "(d) streamlining leasing and permitting processes to expedited exploration, production, processing, reprocessing, recycling, and domestic refining of critical minerals."

On May 18, 2018 under the Executive Order, the Secretary of the Interior, in coordination with other federal agencies, published a list of thirty five "critical minerals," defined as a "non-fuel mineral or mineral material essential to the economic and national security of the United States," the "supply chain of which is subject to disruption," and that "serves an essential function in the manufacturing of a produce, the absence of which would have significant consequences for our economy or our national security" (83 Fed. Reg. 23,295). That list, which will be updated over time, was prepared by the U.S. Geological Survey (USGS), in coordination with the Bureau of Land Management. To develop the list, the USGS used the White House Office of Science and Technology Council's "Mineral Criticality Screening Tool," which was initially published by the White House in 2016 and is updated annually by the USGS [50].

The critical minerals list, in turn, served as the basis of a new federal REE strategy published by the Secretary of Commerce in June 2019 [51].[9] Entitled "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals," the report puts forth six "Calls to Action," twenty-four goals, and sixty one recommendations that "describe specific steps that the Federal Government will take to achieve the objectives outlined in Executive Order 13,817." The "Calls to Action" are:

- ✓ #1 – Advance transformational research, development and deployment across critical mineral supply chains;
- ✓ #2 – Strengthen America's critical mineral supply chains and defense industrial base;
- ✓ #3 – Enhance international trade and cooperation related to critical minerals;
- ✓ #4 – Improve the understanding of domestic critical mineral resources;
- ✓ #5 – Improve access to domestic critical mineral resources on federal lands and reduce federal permitting timelines; and
- ✓ #6 – Grow the American critical minerals workforce.

Call to Action #2 specifically includes not only conventional sources, but also secondary sources (e.g., recycled materials, post-industrial and post-consumer material) and "unconventional sources (minerals obtained from sources such as a mine tailings, coal byproducts, extraction from seawater, and geothermal brines)." The federal strategy notes that while all thirty five of the recently listed critical minerals are produced from conventional mining sources, "some minerals can also be obtained from underutilized secondary and unconventional sources," including coal products (REE Strategy, p. 15).

Thereafter, on July 22, 2019, President Trump made a determination under section 303 of the Defense Production Act of 1950 (DPA) that the "domestic production capability for Rare Earth Metals and Alloys is essential to the national defense" (Presidential Memoranda, July 22, 2019) [52].[10] The DPA, which allows the President to prioritize contracts for materials, equipment and services, has been invoked in the past for technologies, materials and research related to semiconductors, lithium ion batteries and ammunition. The determination specifically applies to: (1) the production of rare earth metals and alloys; (2) the separation and processing of heavy REE; (3) the separation and processing of light REE; (4) the production of neodymium-iron-boron rare earth permanent magnets; and (5) the production of samarium-cobalt rare earth permanent magnets [53].[11] Shortly thereafter, it was revealed that the U.S. Army plans to fund the construction of REE

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[9] https://www.commerce.gov/sites/default/files/2020-01/Critical_Minerals_Strategy_Final.pdf.

[10] https://www.whitehouse.gov/presidential-actions/presidential-determination-pursuant-section-303-defense-production-act-1950-amended-6/.

[11] https://www.miningnewsnorth.com/story/2019/08/01/news/trump-rare-earths-essential-to-us-defense/5845.html; 84 Fed. Reg. 35,967, 35,969, 35,971, 35,973, 35,975.

processing facilities [54].[12] Here again, REE derived from coal byproducts should qualify under one or more of these pronouncements.

With appropriations from the U.S. Congress, the U.S. Department of Energy (DOE) and the National Energy Technology Laboratory (NETL), meanwhile, has been ramping up R&D from unconventional sources under the “Feasibility of Recovering Rare Earth Elements” program [55].[13] That program’s roots go back to 2010, when DOE released the first Critical Minerals Strategy and NETL commenced an initial effort to study the extraction of REE from coal and coal byproducts. The program’s goal is to validate the technical and economic feasibility of small, domestic, pilot-scale, prototype facilities to generate, in an environmentally benign manner, high purity 90–99 wt% (900,000–990,000 ppm), salable, REE oxides from 300 ppm coal-based resources. Since 2014, the program has grown to a funding-opportunities” title = "https://www.netl.doe.gov/coal/rare-earth-elements/program-overview/funding-opportunities">portfolio containing approximately 25–30 active research, development and demonstration (RD&D) projects. Program funding for was at a level of $15 M/year between 2014 and 2018, and was increased to $18 M in 2019.

4.2. Federal legislative developments

The use of PRB coal byproducts as a resource for REE’s also is supported by a half-century of federal non-fuel minerals and materials legislative enactments. Despite this, Congress has not yet enacted a federal law that comprehensively sets federal REE policy, an omission that arguably fails to keep legislators abreast of potentially novel, domestic, abundant, cost-effective and environmentally preferential sources of REE’s such as PRB coal byproducts. This section highlights some, but not all, of the significant legislative actions related to REE’s over the past several decades.

The development of a non-fuel minerals policy “has been a continuing concern since the end of World War II” [56]. Indeed, since 1950 “the subject has been thoroughly examined in a series of major studies by various administrations and presidential or congressional commissions” [57].

On January 22, 1951, for example, President Truman constituted a “Materials Policy Commission” with instructions to “study the materials problem of the United States and its relation to the free and friendly nations of the world” [58]. The Commission delivered in findings in a June 2, 1952 multi-volume report entitled “Resources for Freedom.” The report addressed REE’s, noting economic, technical and waste minimization challenges that still resonate today:

> In working the new bastnäsite deposits, much development work needs to be done to get efficient concentration … There is some fear that, in the expediency of quickly attaining high production volume, wasteful scalping of the deposits and burial of marginal mineral areas may result. To avoid wasteful reworking for overlooked materials, as has happened so many times in the past, it is to be hoped that operators in recovering rare metals from the new bastnäsite deposits will segregate any byproducts of any possible future value (Resources for Freedom, A Report to the President by The President’s Materials Policy Commission, 1952).

The formal legal foundation for U.S. REE policy similarly dates back decades and is rooted in U.S. mineral laws, which “provide a framework for the development of domestic metal mineral resources …. ” [58]. Specifically, in the Mining and Minerals Policy Act of 1970 (MMPA) [59], Congress declared that it was continuing U.S. policy to study and develop “methods for the … reclamation of mineral waste products, and the reclamation of mined land, so as to lessen any adverse impact of mineral extraction and processing upon the physical environment that result from mining or mineral activities.” While this statute does not specifically refer to REE’s, it defines the term “minerals” broadly and specific minerals are the principal economic sources of the REE. By “lessen [ing] any adverse impact from mining or mineral activities”, the use of PRB coal byproducts as an REE source comfortably fits within the broad mining and minerals policy goals of this foundational 1970 law.

Earlier that same year Congress passed the National Materials Policy Act of 1970 (NMPA) [60]. Contemporaneously described as the only federal statute then in existence that directly states a “national materials policy,” the NMPA: (1) established the National Commission on Materials Policy, which helped to convene various technical conferences through the 1970’s; and (2) set as a related policy goal enhancing “environmental qualify and conserve [ing] materials” [61]. Enactment of the NMPA was preceded by a 1969 report by a committee of the Library of Congress entitled “Toward a National Materials Policy” [61]. The report concluded, in part, that the United States should: (1) “husband [its] resources by efficient processing techniques and by the use of commonly available materials as alternatives for materials that may become [in] short [supply]; and (2) ensure that such “operations and activities [be conducted] in such a way as to minimize pollution of air and water … both physical and biological.”

A decade later, in 1980, Congress enacted a more specific policy in the form of the National Materials and Minerals Policy, Research and Development Act of 1980 (NMMA). In the NMMA [62], Congress declared that, notwithstanding passage of the MMPA and NMPA a decade earlier, the United States lacked a coherent national materials and minerals policy. The NMMA introduced the term “materials”, defined as:

> substances, including minerals, of current or potential use that will be needed to supply the industrial, military, and essential civilian needs of the United States for the production of goods and services, including those which are primarily imported or for which there is a prospect of shortages or uncertain supply, or which present opportunities in terms of new physical properties, use, recycling, disposal or substitution, which the exclusion of food and of energy fuels used as such.

With “materials” so defined, the NMMA declared, among other things, that it is the continuing policy of the United States to promote an adequate and stable supply of materials necessary to maintain national security, economic well-being and industrial production with appropriate attention to a long-term balance between resource production, energy use, a health environment, natural resources conservation and social needs. Establishing a policy leadership framework in the executive branch with reports to Congress, the NMMA specifically supported “basic and applied research” in areas such as “improved methods for the extraction, processing, use, recovery and recycling of materials which encourage the conservation of materials, energy, and the environment …. ” Here again, the use of PRB coal byproducts as an REE source – which constitutes a “use, recovery [and/or] recycling of materials” that “encourage the conservation of materials, energy, and the environment” – fits within this more specific “materials” policy framework.

Just four years later, in 1984—and reflecting ongoing concerns with the effectiveness of federal policy— Congress passed the National Critical Materials Act [63] (NCMA). The NCMA was based upon several findings, including that: (1) the Nation’s “industrial base, including the capacity to process minerals and materials, is deteriorating – both in terms of facilities and in terms of a trained labor force”; (2) “research, development, and technological innovation, especially related to improved materials and new processing technologies, are important factors which affect our long-term capability for economic competitiveness, as well as for adjustment to interruptions in supply of critical

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[12] https://www.reuters.com/article/us-usa-rareearths-army-exclusive/exclusive-u-s-army-will-fund-rare-earths-plant-for-weapons-development-idUSKBN1YF0HU.

[13] https://www.netl.doe.gov/coal/rare-earth-elements/program-overview/background.

minerals and materials"; (3) "while other nations have developed and implemented specific long-term research and technology programs to develop high-performance materials, no such policy and program evolution has occurred in the United States"; and (4) "there exists no single Federal entity with the authority and responsibility for establishing critical materials policy and for coordinating and implementing that policy". To help remedy this and other identified deficiencies, the NCMA established a "National Critical Materials Council" to help coordinate federal policy and research in the area, including research under the NMMA [64].

Congress last passed comprehensive energy legislation in 2005 and 2007, when it approved, respectively, the Energy Policy Act [65] and the Energy Independence and Security Act [66]. The latter contained no REE-related provisions, while the former required the U.S. Secretary of Energy, in consultation with the U.S. Secretary of Defense and U.S. Secretary of Homeland Security, to study various topics bearing on international energy security, including China's (via CNOOC Ltd.) then-potential acquisition of Unocal, which owned Molycorp Inc., the then-leading Western resource for lanthanide products [67]. Issued in February 2006, the resulting report concluded that, although the issue was moot because the identified transaction did not occur, federal law authorized the President to block such transactions on national security grounds [67].

On September 18, 2013, the U.S. House of Representatives passed H. R. 761, the National Strategic and Critical Minerals Production Act [68], by a bipartisan vote of 246–178. H.R. 761, which failed to the advance in the U.S. Senate, would have provided expedited permitting and environmental reviews for "mineral exploration or mine permit [s]" including "plans of operation" issued by the Bureau of Land Management and U.S. Forest Service. The legislation did not specifically mention non-fuel minerals and, unfortunately in light of the findings of this study, otherwise seemed to assume that all REE's were produced from conventional mining techniques.

One of Congress' most recent efforts to enact a comprehensive REE bill played out in the U.S. Senate in 2013, with the introduction of S. 1600 by Sen. Murkowski (R-AK), and in early 2014, when the Senate Committee on Energy and Natural Resources held hearings on the bill. Entitled the Critical Minerals Policy Act of 2013 [69], S. 1600 was intended to "facilitate the REE establishment of domestic, critical mineral designation, assessment, production, manufacturing, recycling, analysis, forecasting, workforce, education, research, and international capabilities in the United States .... " (S. 1600, preamble). Numerous provisions of S. 1600 would have supported further assessments and research with respect to PRB coal byproducts as potential REE resources. For example, the bill would have directed the U.S. Secretary of Energy to "conduct a program to identify, research, and develop [REE's] from nontraditional sources .... " (S. 1600, § 206). Other provisions would have advanced the "efficient production, use, and recycling of critical materials throughout the supply chain" in a manner that potentially could have advanced some of the findings set forth in this study (S. 1600, § 206). Unfortunately, S. 1600 failed to further advance in the legislative process.

Since these efforts in 2013 and early 2014, Congress appears to have reverted to efforts to enact REE policy in piecemeal fashion, but again without success. For example, on June 29, 2017, Sens. Murkowski (R-AK) and Cantwell (D-WA) introduced S. 460, the Energy and Natural Resources Act of 2017 [70]. An otherwise comprehensive energy bill building off of legislative momentum for the same, S. 1460 nonetheless lacked comprehensive REE policy provisions and, unfortunately, specifically failed to carry forward the broad REE provisions of S. 1600, discussed above. S. 1460 instead would have: (1) repealed the NCMA (as would have S. 1600); and (2) directed the U.S. Secretary of Energy to conduct basic and applied research on the "efficient use, substitution, and recycling of potentially critical materials in vehicles, including [REE's] and precious metals, at risk of supply disruption" (S. 1460, §§ 1411(a) (22), 3311). S. 1460 would not have applied to stationary renewable energy systems making use of REE's or specifically promote research and development of unconventional REE's such as PRB coal byproducts. This unsuccessful piecemeal approach may reflect the current gridlocked state of affairs in the U.S. Senate vice an explicit backing away from endeavoring to pass comprehensive REE legislation.

5. Conclusion

Based upon initial research and analysis, PRB coal byproducts hold promise as a potential source of economically recoverable REE's especially those with economically favorable geochemistry related to extraction and fuel use. The existing coal byproducts from decades of PRB consumption may in fact already represent a significant REE strategic resource in the United States. As a result, a new strategy to mine PRB coals with slightly increased ash content yet a significant increase in REE resources may be possible. Geochemical interactions influencing coal must be better understood to benefit both the Btu- and REE-values of coal. Research and development of REE extraction from coal byproducts is strongly suggested, not just by this investigation, but other notable studies, and may very well put coal byproducts well within economic reach as a REE resource sooner than later. Much of the extraction research needed is that of a larger scale than bench-scale methods that are already proven.

> The results from the coal byproducts analysis show that there is potential for the extraction of REE from coal byproducts to lead to positive NPVs for coal stations. Additional data and economic research are needed, however, to support the critical assumption that fixed costs associated with extraction are capped at 15 million USD. As a matter of policy, using PRB-based coal byproducts as a research for REE's furthers decades' long efforts by federal and state policymakers to advance this important resource. Informed policy making would provide stronger footing in developing these potential resources if national importance.

Credit author statement

Bagdonas D.A.: Conceptualization and Investigation, Methodology, Formal analysis, Writing – original draft preparation. Enriquez A.J.: Writing – original draft preparation, Methodology. Coddington K.A.: Writing – original draft preparation, Methodology. Finnoff D.C.: Validation, Supervision, Writing – review & editing. McLaughlin J.F.: Supervision, Project administration, Resources, Writing – review & editing. Bazilian M.D.: Writing – review & editing. Phillips, E.H.: Writing – review & editing. McLing T.L.: Funding acquisition, Conceptualization.

Data availability

Datasets related to this article can be found at doi: 10.17632/2znvfsdj3c.**3**, hosted at Mendeley Data, V3, (Bagdonas et al., 2021).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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