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A Fundamental Economic Assessment of Recovering Rare Earth Elements and Critical Minerals from Acid Mine Drainage Using a Network Sourcing Strategy

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Abstract: In recent years, acid mine drainage (AMD) has emerged as a promising unconventional source of rare earth elements (REEs) and other critical minerals (CMs) such as cobalt and manganese. In this regard, AMD provides a natural heap leaching effect that extracts and concentrates REE/CM from the host strata creating a partially enriched feedstock suitable for downstream extraction, separation, and recovery. While several prior studies have described processes and approaches for the valorization of AMD, very few have described the supply chain and infrastructure requirements as well as the associated economic assessment. To that end, this paper provides a fundamental economic assessment of REE/CM recovery from AMD using a network sourcing strategy in addition to a robust, flexible feedstock separations and refining facility. The methodology of this paper follows that of a typical techno-economic analysis with capital and operating costs estimated using AACE Class IV (FEL-2) guidelines. To demonstrate the range of possible outcomes, four pricing scenarios were modeled including contemporary prices (September, 2021) as well as the minimum and maximum prices over the last decade. In addition, five production scenarios were considered reflecting variations in the product suite, ranging from full elemental separation to magnet REE and CM production only (i.e., Pr, Nd, Tb, Dy, Y, Sc, Co, and Mn). The results of this analysis show that, with the exception of the minimum price scenario, all operational configurations have positive economic indicators with rates of return varying from 25% to 32% for the contemporary price scenario. The optimal configuration was determined to be production of Co, Mn, and all REEs except for mischmetal, which is not recovered. Sensitivity analysis and Monte Carlo simulation show that capital cost and HCl consumption are the two major factors influencing rate of return, thus indicating opportunities for future technology development and cost optimization. Implications of the study and a cooperative profit-sharing model for sourcing are also described.

Keywords: techno-economic analysis; rare earth elements; acid mine drainage; solvent extraction; critical materials; cobalt; manganese

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1. Introduction

Over the last decade, critical minerals have become an increasingly important matter of both technical and societal importance. While several US federal and international agencies (e.g., U.S. Departments of Energy, Commerce, Defense, USGS, the European Commission, the International Energy Agency, Geoscience Australia, etc.) have provided precise definitions for mineral criticality, they all generally capture the combined factors of importance to modern society and risk for supply chain disruptions [1–7]. Many public and private organizations have developed policies and investment strategies to de-risk critical minerals production, and this trend is expected to continue over the next several decades as the demand for electric vehicles, lightweight batteries, and consumer electronics intensifies. In addition, several US federal agencies have developed early-stage research and development programs to identify alternative and unconventional critical mineral resources. To this end, this study addresses the economic potential of recovering critical minerals from acid mine drainage (AMD), a deleterious byproduct of many mining operations.

One specific subset of critical minerals include several of the rare earth elements (REEs). In general, the REEs, or lanthanides, are a group of 15 elements from La to Lu and often include Y and Sc as they share similar physical and chemical properties. According to the USDOE, the REEs Nd, Dy, Tb, Eu, and Y are considered critical, given their importance in renewable energy technologies. For this paper, the REEs will be further divided into light-REE (LREE), mid-REE (MREE) and heavy-REE (HREE) categories. La, Ce, Pr, and Nd are considered LREEs; Sm, Eu, and Gd are considered MREEs; while other REEs, Y and Sc, are considered HREEs. While not rare in terms of crustal abundance [8,9] REE are rarely found in significant concentrations. This phenomenon is especially true for HREE and scandium. The dispersed nature of REEs therefore limits the economic potential of REE mining and as expected, most of the world production of LREEs and MREEs is generated as the by-product of iron mining at the Bayan Obo mine in northern China. The majority of the world production of HREE is, in contrast, obtained through in situ leaching of ion-absorption clays in southern China and Myanmar [10].

The dependence of the United States on Chinese suppliers is deemed a threat to American sovereignty and a critical vulnerability to its military. The US Senate Bill S.1317—American Mineral Security Act was introduced to support the recovery of critical minerals [11]. Global awareness on the supply risks related to REE were first raised during the 2010-2012 restrictions on exports coupled with increasing worldwide demand due to technological applications [12]. Subsequent easing of the export quotas following a period of massive delocalization of the REE supply chain to China and the consolidation of the industry [13] resulted in the bankruptcy of most junior mining companies formed to provide an alternative supply of REE [12].

Given these factors, many countries, including the U.S., initiated intensive research and development campaigns to identify unconventional REE resources and to develop the process technologies needed for extraction and separation. One such program, funded by the U.S Department of Energy, evaluated coal byproducts, including coal mine drainage as a potential feedstock for REE recovery [14–16].

Acid mine drainage is a well understood phenomena occurring due to the weathering of sulfide minerals resulting in the in situ production of sulfuric acid. The acid then leaches metals in the surrounding strata and discharges to nearby streams, damaging the environment [17,18]. AMD often contains high concentrations of "regulated" metals, such as Fe, Al, and Mn; however, Vass et al. demonstrated that a significant amount of valuable REE are also solubilized in Appalachian coal-based AMD [19,20]. Surveys in different areas of the world resulted in different, but nevertheless significant REE amounts. Leon et al. estimated the annual REE value of the Iberian Pyrite Belt discharges at 24.1 MM USD [21] while Migaszewski et al. reported REE concentrations up to 24 ppm from the Wiśniówka mining area in Poland [22].

As indicated by Vass et al., AMD pH is the single best predictor of REE load, with a clear distinction at pH of 4 to 5. AMD above this range typically has low or negligible REE concentrations, often less than 100 ppb, while AMD below this range shows higher concentrations up to ppm levels. AMD discharges with low pH water, containing higher levels of metal ions usually are treated using active treatment processes [23,24]. Alkali neutralization of AMD is one of the most widely used remediation process [24], with lime being usually the most cost effective reagent. In the lime neutralization process, the AMD is neutralized with quicklime or hydrated lime while being aerated, precipitating all metals from the water [24–26]. A comprehensive review on AMD treatment technologies has been provided by Skousen et al. [27]. Regardless of the treatment approach, AMD is often viewed as a nuisance waste and an obvious cost center for mining operations. Incentivization of AMD treatment through valorization could thus represent a paradigm shift away from the conventional compliance-based approaches.

The notion of the circular economy, as related to sustainable development, has gained traction in various sectors of society such as in governments, businesses, NGOs, and academia [28–30], while the concept still has some ambiguity in practice [28], it has recently been associated with the recovery of metals from AMD sources. In this conceptualization, AMD is seen as a resource rather than as a waste stream [26,31,32]. The high concentration of iron and aluminum initially attracted investigation into the recovery of those metals. Wei et al. demonstrated that high recovery of both metals was possible in lime neutralization systems, albeit at a purity in the low 90% range [33]. The production of high purity iron products from AMD was demonstrated by reprocessing the low purity sludge using nitric acid and potassium hydroxide [34] and alternatively through the usage of high cost soda ash neutralization agent [35]. Both options however require expensive reagents to yield low value products. As such, very few if any such commercial projects have been deployed worldwide.

In addition to base metals, high value critical materials can also be recovered from AMD. Specifically related to the rare earth elements, Ayora et al. showed how REE could be recovered to the basaluminite portion of their passive treatment unit [36]. Felipe et al. used cationic resins to recover REE from AMD using ion exchange. However, the resin used favored low value lanthanum and LREE over valuable HREE [37]. Many sorbants have been evaluated to specifically recover REEs from AMD and sorption literature has been recently discussed by both Wei et al. [38] and by Royer-Lavallee et al. [39]. No specific sorption process has been shown to hold economic promise at scale.

In other studies, researchers have shown that REEs can be effectively recovered from acid leachate generated from coarse coal reject [40–42]. In once case, Zhang and Honaker were able to generate a 94% mixed rare earth oxide product through multi-staged precipitation and re-dissolution of natural leachate from a coarse coal waste pile [40]. In a second study, Zhang and Honaker produced a 98% mixed rare earth oxide product along with Cu, Ni, and Co co-products [41]. A comprehensive review on these and other similar studies on coal-based leachates has been provided by Zhang et al. [40–43].

The economic potential of recovering REEs from AMD and AMD precipitate using a selective multi-step leaching process was evaluated by Fritz [44]. This study showed that process and operational configuration employed by the researchers were not economically viable at the proposed scale (1000 kg REE/yr) without significant government subsidies. Despite this finding, Fritz et al. provided a valuable framework for subsequent project evaluations. It should also be worth noting that few studies to date have also addressed the simultaneous recovery of REEs and other non-REE CMs, which could significant increase the value proposition.

Recently, an effective AMD treatment process was developed and patented by West Virginia University to recover REE and other critical minerals from AMD as a pre-concentrate using a two-step precipitation approach [45]. In this process, the AMD stream is first neutralized to a pH of 4 to 4.5 to precipitate all iron and most aluminum. The resulting solution is further neutralized to a pH 8 to 8.5 to precipitate all REE with most cobalt and manganese as a pre-concentrate material. The REE/CM depleted water is sent to the permitted discharge point, meeting applicable clean water standards as set by the relevant local, state, and federal agencies. Processes derived from the work of West Virginia University have been investigated by others such as Moraes et al. investigating the role of A13-polymers in the neutralization process [46]. Moraes et al. concluded that aluminum polymers play a role in the losses of REE to tailings in specific ranges of pH. Their data set is consistent with the West Virginia University Process.

The objective of the present study is to provide a high-level assessment of the economic merits of recovering REE and select CM from AMD sources using an innovative decentralized network supply chain configuration. This approach relies on two enabling technologies: (1) an on-site pre-concentration process that produces an upgraded, dry REE intermediate suitable for transport; and (2) a centralized separation and refining circuit that allows full REE separation at a capital cost significantly below that of conventional approaches. To meet this objective, the study will provide a detailed analysis of the process cost drivers and the sensitivity with respect to different operational configurations and price scenarios.

2. Materials, Process, and Methods

2.1. Process Description

The rare earth element and critical minerals recovery process used in this analysis was developed by L3Eng in collaboration with West Virginia University and Virginia Tech using pre-concentrate material generated by a patented two-step acid mine drainage (AMD) neutralization process [45]. Since the AMD neutralization process only requires a reconfiguration of the standard AMD treatment process and does not significantly increase its operating cost, it has not been included in this analysis; however, the cost to transport the pre-concentrate to a centralized refining plant is included as a variable operating cost. It should be noted that not all AMD sources are conductive to the recovery of REE and that the study only included those sources with sufficient REE concentration. AMD sources with marginal concentrations of REE may be added to the project at a later stage should their impurity profile allow for the concentration of REE in the pre-concentrate material at levels similar to included sources.

Testing to date on a variety of AMD sources have shown that the pre-concentration process typically produces an REE precipitate averaging 1% to 5% in grade with moisture as low as 15%. Figure 1 shows the REE/CM elemental assay for a pre-concentrate sample produced from an active AMD discharge near Bismarck, WV using the process described in US Patent US20210017625A1 [45]. Assays for this sample were determined by the NRCCE laboratory in Morgantown, WV, using the method described in Vass et al. [19]. As shown, the pre-concentrate contains a significant portion of heavy and critical REEs, with the most abundant element being Y. La and Ce are notably reduced while Dy is increased in this material when compared to conventional REE ore sources. Using current REE pricing, the basket price for this material (including only Sc, Y, and the lanthanides) is determined to be: \$60.76/kg, which is extremely competitive with and superior to many conventional REE deposits.

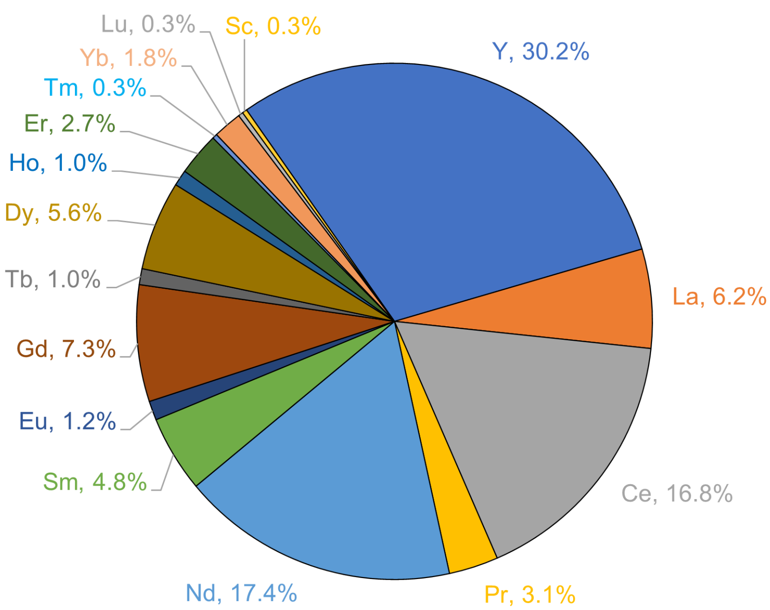

Figure 1. Composition of pre-concentrate material generated at Bismarck, WV, AMD treatment facility.

After generating pre-concentrate at a number of distributed sites, the material is transported by truck to a central extraction and refining plant. A block flow diagram for the full process is shown in Figure 2. First, the pre-concentrate is leached using hydrochloric acid and the pregnant leach solution is partially neutralized using sodium carbonate. The resulting aqueous solution is processed in a series of solvent extraction units to separate the rare earth elements, cobalt and manganese. Commercially available extractants including Di-(2-ethylhexyl)phosphoric acid (D2EHPA), 2-ethylhexyl phosphoric acid mono-2-ethylhexyl ester (EHEHPA), sec-octyl phenoxyacetic acid (CA-12), Cyanex 272 (C-272), and Cyanex 572 (C-572) are used in the flowsheet to facilitate the full separation of REEs. The team is exploring reduction processes including one developed by Hela Novel Metals. In this process, rare earth elements and cobalt oxalates are reduced to rare earth and cobalt metals and formed into magnets using their proprietary patent pending Carboxylate Reduction Process (CRP) [47].

The rare earth element recovery units consume hydrochloric acid, ammonium hydroxide, oxalic acid, zinc pellets, sodium hydroxide, and sodium carbonate while the cobalt recovery unit consumes ammonium hydroxide, sulfuric acid, and oxalic acid. The manganese recovery unit consumes calcium oxide (quicklime) and an internally recycled oxidizing agent. The Hela Novel metals process utilizes a proprietary mixture of nitrogen, ammonia, carbon monoxide and hydrogen.

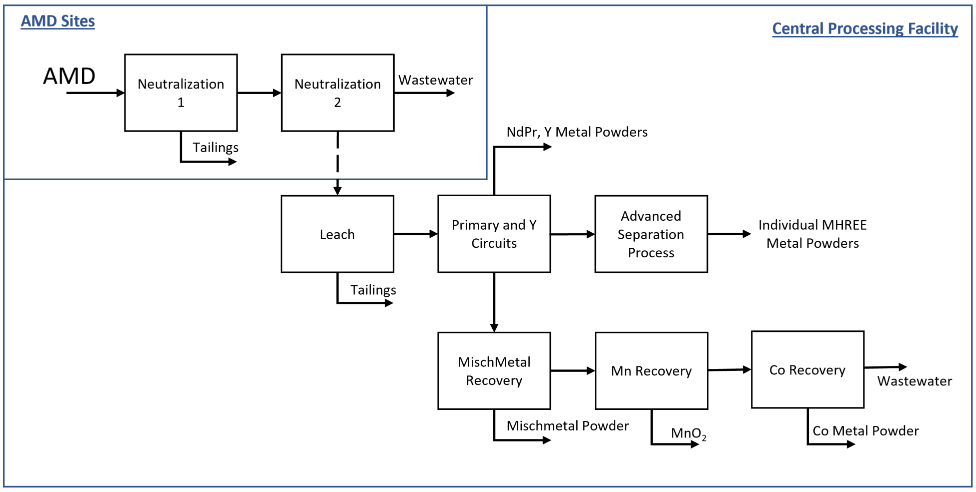

Figure 2. Proposed block flow diagram.

2.2. Techno-Economic Analysis for the Recovery of REEs and CMs from AMD

The techno-economic analysis was performed on a conceptual extraction and refining process designed using a combination of theoretical equilibrium calculations [48] and bench scale test work. This method is typical of an innovative process flowsheet development and design project using the Front-End Loading (FEL) process [49]. In this process, the economic viability of the proposed project is evaluated at various project advancement stages, each with increasing investment in time, material and capital. The FEL process was developed to minimize the overall project investment risk [50].

Economic assumptions, including those regarding the financing structure, escalation rates, tax calculations, and operating period include:

- All amounts are in USD.
- The total operational period for the plant is 20 years.
- Inflation was applied to sales revenue and operating costs using a fixed rate of 3% per year.
- Capital costs are spread over a period not to exceed three years, and the allocation between those three years is 10%, 60%, and 30% for years one through three, respectively. Thus, the total analysis period (capital purchase plus operating) is not to exceed 23 years.

- During the capital expenditure period, capital costs escalate at a constant rate of 3.6% per year.
- The project is debt financed for 50% of the total overnight capital requirement; the remaining 50% is financed by equity.
- The debt repayment terms include: 6% interest rate, 10-year loan period, and no grace period on debt repayment. The re-payment uses a standard amortization schedule with constant payments throughout the payoff period.
- Working capital is not included in this estimate and will instead be borne by the operating entity at no cost to the project.
- The combined federal and local tax rate is fixed at 26%.
- All capital is depreciable, using a 150% declining balance depreciation schedule over 20 years. The depreciation method was not changed to straight line when conditions favored the switch.
- The mineral depletion rate for REEs is 14%. Depletion is charged at the appropriate rate times the net sales revenue after deducting royalties and any severance tax, provided that the total amount calculated by depletion rates does not exceed 50% of the taxable income before depletion.
- The plant is part of a larger commercial entity with sufficient revenue to offset negative taxable income. Thus, losses are not carried forward and are instead calculated as a "negative tax" that indicates the reduction in tax burden required for overall entity.
- No royalties are charged for the productions of REEs, as this cost is assumed to be borne with the feedstock acquisition costs.
- All production is assumed to be sold.

2.2.1. Operating Cost Estimate

The operating cost is calculated based on four generic cost categories.

- Materials, Reagents, and Consumables;
- Energy;
- Labor;
- Capital Spares.

Reagents, consumables, and energy costs were derived from a process heat and material balance, simulated using the commercial simulation program METSIM. When available, bench scale test data was used as a basis for the simulation. When not available, or not practical for the stage of development of the project, literature and thermodynamic simulations were utilized. The solvent extraction circuit, however, was simulated using a simulation method previously developed by the author and described elsewhere [48] using literature data as a basis. The separation factors inputted to the model were derived from the literature and are presented as Table 1.

Electrical energy costs are primarily consumed by the pumping and agitation. The process plant will also consume natural gas for process heating purposes through hot oil heaters. Labor costs have been estimated for staffing numbers typical for similar plants based on the experience of the design team. At any given time, 17 full time employees are required for the plant operation and maintenance activities, while water treatment costs have been included using typical costs, other waste disposal costs have not been included in the analysis. Capital spares have been estimated at 4.0% of the purchased equipment cost annually.

Bench-marking of the process flowsheet was not possible since no commercial operation is currently extracting and refining REEs and CMs from AMD, and because both the process flowsheet and the process throughput is significantly different than commercial operations. Commercial separation plants typically have capacities in the thousands to tens of thousands of tonnes per year and operate a continuous process with dedicated circuits for each element. These plants also tend to have rigid guidelines for feedstock compositions with little short term flexibility. Our process is at least an order of magnitude smaller than commercial operations, has both continuous and semi-continuous circuits with a built-in flexibility for the processing of different feedstock compositions.

Table 1. Model separation factors. ("*" denotes factors not reported).

	EHEHPA	CA-12	CA-12,C272	C-572
Source	[51]	[52]	[52]	[53]
Reference Element	La	Y	Y	La
La	1	*	*	1
Ce	6.8	*	*	5.9
Pr	13.9	*	*	9.5
Nd	21.5	*	*	14.6
Sm	227.8	*	*	101
Eu	341.7	*	*	189
Gd	1982	3.73	1.97	252
Tb	>2000	3.09	1.86	612
Dy	>2000	2.44	1.75	1014
Ho	>2000	1.73	1.41	1308
Er	>2000	1.67	1.65	2013
Tm	>2000	1.36	2.51	3961
Yb	>2000	1.25	5.09	5611
Lu	>2000	1.06	6.55	9583
Y	>2000	0.15	0.05	1713
Sc	>2000	8.00	8.00	38,334

2.2.2. Capital Cost Estimate

The capital cost estimate was developed following the AACE Class IV (FEL-2, or =/−40%) level engineering study cost estimate guidelines. Process equipment was sized based on the heat and material balance for the process and design criteria either derived from bench scale test work or based on the design engineer's experience for this type of process. The estimate uses major unit operation supply costs factored to installed unit cost, assuming a greenfield generic industrial site. Non-equipment related direct costs are factored using the Peters and Timmerhaus Method [54] based on the design engineer's experience for this type of process. Other direct cost factors are included in Table 2.

Table 2. Other direct costs factors.

Direct Cost	Typical Range	Selected Factor
Instrumentation and Controls	10%–20%	10%
Piping	20%–70%	15%
Electrical	10%	10%
Building and Structure	20%–30%	20%
Property Improvements	10%	10%
Utilities	20%–50%	20%

Most factors were selected at the lower end of the typical range due to the nature of the process. Notably, the large majority of the plant piping will be composed of small diameter plastic or FRP piping because the process involves small flow rates at low temperature and low pressures. Required instrumentation will be mostly located at the feed and discharge of the solvent extraction batteries, resulting in a relatively low instrument factor.

Where possible, budget pricing for major cost items have been obtained from vendors based on preliminary specifications developed during engineering. Alternatively, where recent and relevant project data enables an item to be estimated it may be based on that information. Where neither is possible, equipment pricing was obtained from engineering databases. When none of the above was available, allowances were assigned based on experience and judgment of the engineers involved in the study.

Indirect costs were factored on the direct costs and have magnitudes selected to account for the characteristics of the project.

Owner's costs have been assigned according to the design engineer's experience for projects of this type. The scope of Owner's costs included is limited to those defined and other areas of expenditure may be required.

2.2.3. Financial and Sensitivity Analysis

Life cycle financial analyses were conducted using several REE pricing scenarios as shown in Table 3. The baseline case uses 2020 prices, while the additional cases utilize 2021 prices as well as the minimum and maximum prices over the last decade. Given the extreme volatility over this date range, these values are anticipated to represent the limiting thresholds for analysis.

In addition to the pricing scenarios, five distinct plant configurations were also considered. These include:

- Complete Processing Plant (REEs, Co, Mn, and mischmetal);
- REE plant, with no mischmetal;
- REE, Co plant, with no mischmetal;
- REE, Co, Mn plant, with no mischmetal;
- Only salable products are the magnet REEs (Pr, Nd, Tb, Dy), Y, Sc, Co and Mn.

Table 3. Pricing Scenarios used for Analyses, all values in USD/kg.

Product	2020 Price	2021 Price	Min Price	Max Price
MREO	$26.65	$39.05	$16.13	$47.46
M-HREO	$73.22	$117.47	$46.93	$143.12
Nd(Pr) micro powder	$69.65	$129.11	$51.60	$129.11
Y Metal micro powder	$39.77	$40.13	$24.72	$40.13
Mischmetal micro powder	$20.45	$4.89	$3.27	$20.45
Cobalt micro powder	$41.67	$58.60	$23.77	$58.60
Sm micro powder	$18.40	$15.01	$13.25	$15.01
Crude EuSO4	$7.50	$7.87	$7.45	$7.87
Gd metal micro powder	$56.81	$72.31	$24.21	$72.31
Tb metal micro powder	$738.58	$1867.41	$511.19	$1867.41
Dy metal micro powder	$340.88	$579.23	$251.59	$579.23
Ho metal micro powder	$695.03	$768.62	$315.14	$768.62
Er metal micro powder	$107.95	$116.66	$39.24	$116.66
Tm metal micro powder	$857.29	$925.77	$379.57	$925.77
Yb metal micro powder	$228.28	$229.18	$93.96	$229.18
Lu metal micro powder	$3298.76	$3451.32	$1415.04	$3451.32
Sc metal micro powder	$3976.99	$3314.83	$1359.08	$3314.83
Manganese oxide	$1.97	$1.97	$1.58	$3.20

For the purpose of this analysis, an average pre-concentrate composition building on work by Vass et al. and Ziemkiewicz et al. was assumed. Therefore, no alternative scenario based on variations of feed composition was considered. The composite pre-concentrate composition is presented as Table 4. It has been estimated that approximately 53,000 mtpy of pre-concentrate material will be required to supply a refinery operating at its design capacity. This value translates into approximately 104,500 cubic meters per hour of treated AMD capacity, which is well within the limits of the estimated flows of the survey by Vass et al., especially when supplemented by other coal-based AMD surveys [55,56] and hard-rock AMD sources [57]. Based on the composition, a maximum contained value assuming full separation and conversion to products was calculated for the four pricing scenarios and is presented as Table 5; the contained value indicates the aggregate value of a ton of pre-concentrate material assuming complete recovery of each salable product, while not particularly useful in itself, the contained value metric allows for the comparison of projects with each other and offer an indication of processing efficiency when compared to the (realized) pre-concentrate value discussed in a later section of the article.

Table 4. Pre-concentrate composition.

Element	Composition
Al	5.03%
Si	19.03%
S	3.93%
Ca	4.92%
Sc	0.002%
Mn	13.32%
Fe	8.62×10^{-7}%
Co	0.390%
Y	0.219%
La	0.077%
Ce	0.220%
Pr	0.030%
Nd	0.148%
Sm	0.038%
Eu	0.010%
Gd	0.053%
Tb	0.008%
Dy	0.046%
Ho	0.009%
Er	0.022%
Tm	0.0028%
Yb	0.016%
Lu	0.002%

Table 5. Pre-concentrate contained value in USD/kg.

	2020 Price	2021 Price	Min Price	Max Price
Pre-Concentrate Contained Value	$1242	$1575	$751	$1786

A sensitivity analysis was performed by Monte Carlo simulation using Crystal Ball as an add-on to Microsoft Excel. Triangular probability distribution functions were established for the pricing of the various raw materials and consumables. The minimum and maximum of the functions were set, respectively, to the minimum and maximum market prices for the period 2014 to 2021. Raw material pricing were derived from both publicly available sources such as the USGS commodity survey and private market pricing databases including but not limited to Intratech and Echemi.

Uniform probability distribution functions were established for water treatment and energy costs. With minimum and maximum set in the range 80%–120%. Energy costs were derived from publicly available utility data.

Capital costs for the various scenarios were assigned normal probability distribution functions with a 95% confidence interval approximating the upper and low bounds of the +/−40% precision of the capital cost estimation method.

Revenues are calculated from production quantities derived from the heat and material balance and market pricing. The market pricing was evaluated based on publicly available databases as well as private pricing databases such as Roskill, Asian Metal Prices and ISE. When applicable, factors based on proprietary market pricing data from Hela Novel Metals LLC were applied to account for the specific nature of the products.

Four pricing scenarios were evaluated:

- September 2021 Pricing;
- December 2020 Pricing;

- Minimum Pricing, Period 2014–2021;
- Maximum Pricing, Period 2014–2021.

The three main elements evaluated as part of the financial analysis are the net present value (NPV), the internal rate of return (IRR) and the realized value of pre-concentrate material.

The net present value is the sum of all cash flows incurred or generated by the project discounted to the present using a discount rate defined by the analyst. In the present analysis, a 10% discount rate has been applied to all NPV calculations. It is common to indicate the discount rate in parenthesis following the NPV abbreviation. As such a NPV calculation utilizing a 10% discount rate would be noted NPV (10%).

The internal rate of return is the measure of a discount rate that results in a neutral net present value, NPV(IRR) = 0. It offers an indicator to the project management relative to the project profitability and is often compared to a minimum required rate based on risk profiles [54].

The value of pre-concentrate material is a measure of the level of incentive the project could offer the various AMD neutralization plants to convert their plant to generate pre-concentrate material, assuming the project is operated to meet a IRR of 10%. The basis assumption underlying this metric is a processing pant operating as a cooperative or public service to support the treatment of AMD sources through re-distribution of profits to operators of AMD sites relative to their contribution in feed material quantity and quality. The 10% IRR baseline will provide sufficient capital for improvement projects and to manage market needs.

3. Results, Discussion, and Recommendations

3.1. Engineering Study Summary

A summary of the engineering effort is presented in Tables 6–8, representing the capital and operating cost estimate, production and revenues for each scenarios identified in the previous section.

The operating cost for the four plant configurations is broken down in Figure 3, revealing that raw materials, notably hydrochloric acid and various alkalis, are the most important operating cost. This is typical of rare earth solvent extraction processes which are significant consumers of acids and alkalis [58].

Table 6. Capital and operating cost summary.

Plant Configuration	Capital Cost MM USD	Operating Cost MM USD/Year
Complete Facility	$185.81	$21.35
REE, w/no Mischmetal	$130.79	$17.54
REE, Co, w/no Mischmetal	$148.60	$18.50
REE, Co, Mn, w/no Mischmetal	$154.83	$20.47
Magnet REE, Y, Sc, Co, Mn	$142.20	$20.47

Table 7. Annual REE/CM production for various operational configurations.

Plant Configuration	REE mtpy	Co mtpy	Mn mtpy
Complete Facility	444	157	5653
REE, w/no Mischmetal	290	-	-
REE, Co, w/no Mischmetal	290	157	-
REE, Co, Mn, w/no Mischmetal	290	157	5653
Magnet REE, Y, Sc, Co, Mn	212	157	5653

Table 8. Annual plant revenues for various operational configurations and pricing scenarios.

Plant Configuration (in MM USD)	September 2021	December 2020	Minimum 2014–2021	Maximum 2014–2021
Complete Facility	$70.46	$56.07	$33.39	$79.83
REE, w/no Mischmetal	$49.42	$35.26	$20.25	$49.42
REE, Co, w/no Mischmetal	$58.59	$41.78	$23.97	$58.59
REE, Co, Mn, w/no Mischmetal	$69.70	$52.92	$32.89	$76.68
Magnet REE, Y, Sc, Co, Mn	$56.58	$40.77	$27.58	$63.55

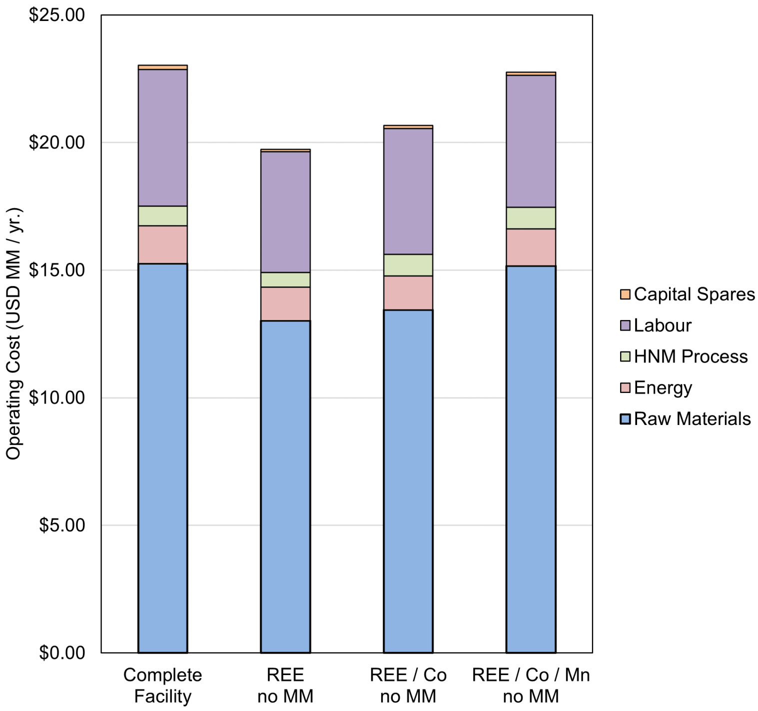

Figure 3. Operating cost breakdown for various operational configurations.

3.2. Financial Analysis

The three main elements evaluated as part of the financial analysis were the net present value (NPV), the internal rate of return (IRR) and the value of pre-concentrate material (PCV).

The net present value, internal rate of returns and pre-concentrate value of the project for the various plant configurations and pricing scenarios assuming a 10% discount rate are presented in Figures 4–6.

While all three elements of the financial analysis yield the same conclusion since they portray the same patterns, key project insight can be derived from the specific indicators IRR, NPV, and PCV. Based on the analysis, the plant configuration where all REEs (except for mischmetal), Co and Mn are produced should be favored and all products should be marketed because it yields the highest IRR and NPV in all comparable pricing scenarios. However, it should be noted that while this plant configuration yields positive returns for all pricing scenarios, it fails to meet the minimum internal rate of return of 10% in the minimum pricing scenario.

Of particular interest is the scenario where only magnet materials, scandium, yttrium cobalt and manganese are sold as products since it represents a more likely scenario since all these products are forecast to be in short supply for the next decade [10]. Even with the minimum pricing scenario, this plant configuration yields a positive return.

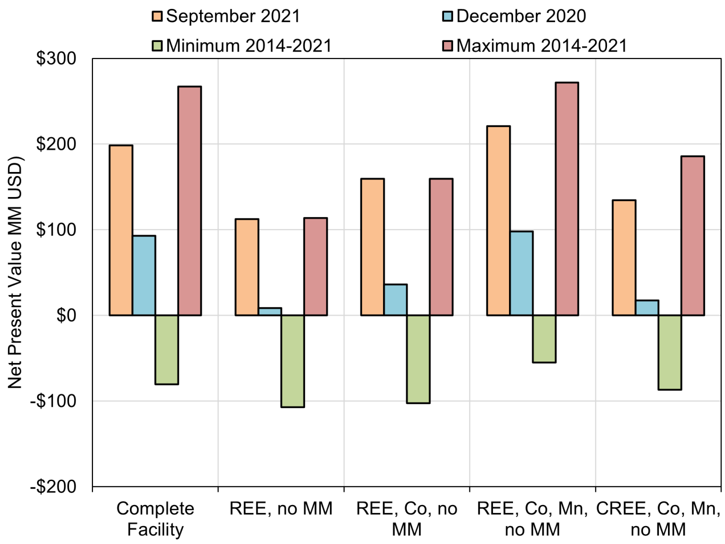

Figure 4. Net present value results for various operational configurations and pricing scenarios.

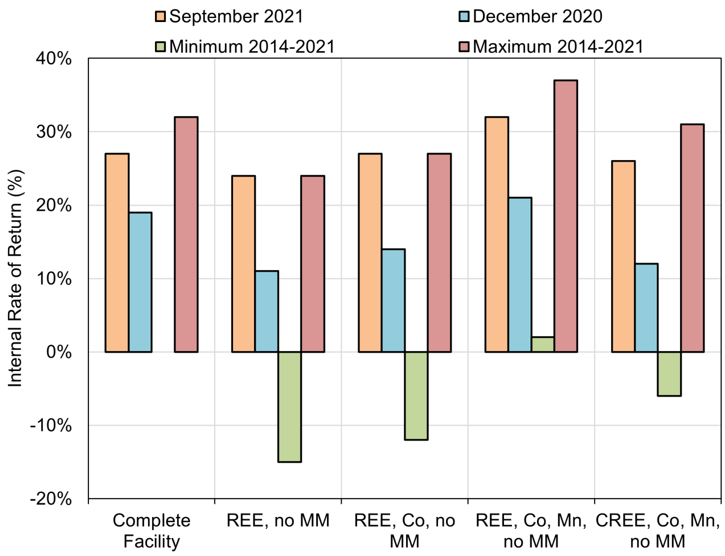

Figure 5. Internal rate of return results for various operational configurations and pricing scenarios.

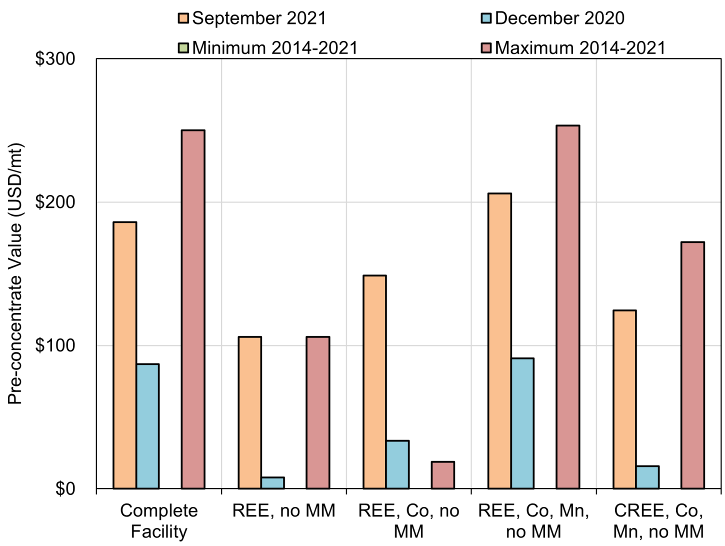

Figure 6. Pre-concentrate value results for various operational configurations and pricing scenarios.

3.3. Sensitivity Analysis

A sensitivity analysis was performed on the magnet REEs, scandium, yttrium, cobalt, and manganese scenario using current pricing for revenue determination. The results of the sensitivity analysis are presented as a Tornado Plot in Figure 7 and in the Monte Carlo summary in Figure 8.

Figure 7. Tornado plot showing the sensitivity of several key input factors on the project rate of return. Current pricing, magnet element-only configuration.

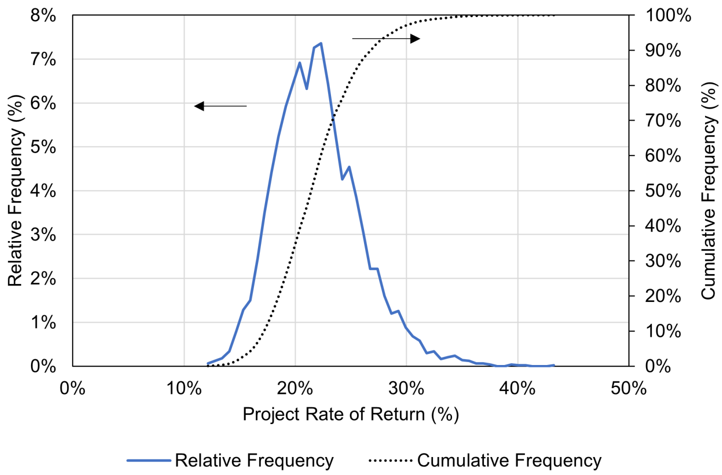

Figure 8. Results from Monte Carlo simulation showing rate of return. Current pricing, magnet element-only configuration.

The tornado plot clearly demonstrates that only two project parameters have a significant impact on the profitability of the project, the capital cost of the project and the pricing of hydrochloric acid. The Monte Carlo analysis reveals that the sensitivity of the project tends to be distributed as a normal distribution centered toward the base pricing internal rate of return with a minimum return around 18% and a maximum return of 35%. The normal distribution of the result is primarily due to the disproportionate effect of the capital cost on the financial indicators studied.

The major takeaway from the sensitivity analysis suggest that any optimization work should be directed at reducing the capital cost of the project and the hydrochloric acid consumption. Both aspects could be simultaneously optimized with a transition to ionic liquids [59] and an optimization of the processing circuit, leaving most heavy elements as a mixture to be stockpiled or processed as needed. Furthermore, the possibility of recycling chlorides from the wastewater streams should be evaluated with respect to hydrochloric acid pricing and a recycling process economic parameters.

3.4. Implication of the Results

Our study proposes an economically viable and sustainable low volume supply chain for critical minerals and rare earth elements aimed at securing these critical minerals for national security purposes, while the economic indicators are favorable in several scenarios, the analysis suggests a level of risk unacceptable for private enterprise, especially considering the base assumption of free sourcing for pre-concentrate and the potential for price volatility including long periods of low market price. We contend that by reframing the sourcing strategy of pre-concentrate from a supplier-buyer relationship to a distributed cooperative supply chain, private corporations as well as government agencies will be incentivized in treating acid mine drainage sources to the benefit of communities downstream of the AMD sites. Moreover, this approach provides a mechanism that both incentivize AMD treatment and promotes economic development in regions that have been most impacted by declining coal production, while mitigating a national security need.

The low concentration of REE in AMD limits the scope and size of the central processing plant, as well as the number of such plants per geographical area. Nevertheless, it is likely that the concept could be duplicated in other mining districts, particularly those with pervasive and perpetual acid mine drainage issues. Ongoing study by the authors indicates substantial AMD based REE/CM in other U.S. mining districts. Future analysis will indicate the extent to which they could add to a national supply chain with respect to recovery, compatibility and economic return.

4. Conclusions

This study has described a detailed techno-economic analysis of a REE/CM supply chain based solely on acid mine drainage feedstocks. Key enabling technologies of this approach include (1) an on-site pre-concentration process that produces an upgraded, dry REE intermediate suitable for transport; and (2) a centralized separation and refining circuit that allows full REE separation at a capital cost significantly below that of conventional approaches. The current study has assessed the capital and operating costs of the centralized separations and metal production plant and used sensitivity analysis and stochastic simulation to identify the major cost drivers. In addition, scenario modeling was used to evaluate the influence of REE/CM pricing and to identify the optimal product suite under various market conditions. Key conclusions from this work include:

- The contained value of pre-concentrated AMD produced from passive two-stage precipitation (US 2021/0017625 A1) ranged from USD 751 to USD 1786 per metric ton when using the minimum and maximum prices over the last decade. The contained value was determined to be USD 1575 per metric ton using contemporary (September 2021) prices. These values are commensurate with or even superior to conventional REE ore deposits currently under consideration.
- The REE basket price of AMD pre-concentrate was determined to be USD 60.76/kg REE when using contemporary oxide prices. This value is nearly two times that of conventional REE sources, including ion adsorption clays found in South China [60]. This value is largely due to the high content of critical and magnet REEs, including Y, Nd, Pr, and Tb, which collectively constitute over 54% of the total REE content.
- Depending on the plant configuration, the production capacity ranges from 212 to 444 mtpy REE, 157 mtpy Co, and 5653 mtpy Mn. This value is significantly below that of conventional REE separation plants; however, this level of production may be crucial in establishing a baseline for national security purposes. An assessment of the pre-concentrate feed requirements needed for this level of production show that the volume is well within the estimated flows of AMD within the Appalachian region.
- The results of this analysis show that, with the exception of the minimum price scenario, all operational configurations have positive economic indicators with rates of return varying from 25% to 32% for the contemporary price scenario. The optimal configuration was determined to include production Co, Mn, and all REEs except for mischmetal, which is not recovered. The magnet REE, Sc, Y, and CM-only configuration, which is deemed to be the most likely given future demand scenarios, yielded a positive rate of return in all scenarios.
- Sensitivity analysis and Monte Carlo simulation demonstrate that the project capital cost and HCl consumption were the only two project parameters that produced a significant impact on overall profitability. This result suggests that further optimization of process design may impart significant financial gains to the enterprise (i.e., the low capital cost estimate produce a 5 percentage point increase to rate of return). Notably, additional research and development on the use of ionic liquids [59], rather than solvent-based extractants may produce simultaneous and synergistic improvement of these two parameters.
- While the economic results are moderately favorable under most scenarios, the level of project risk is significant, particularly considering the possibility of prolonged price disruptions. To mitigate this risk, one option could re-frame the sourcing strategy to one of supplier-buyer cooperative whereby the profits are shared between the investor, the operator, and the feedstock suppliers. Given the nature of AMD treatment in the US, which can often include a mix of government and private liability holders, this approach would inevitably require strong public-private partnerships. Nevertheless, this approach will both incentivize AMD treatment and promote economic development in regions that have been most impacted by declining coal production, while mitigating a national security need.

- To better identify and quantify the environmental, social, and governance, benefit of the proposed approach, additional study should address stakeholder assessments, regional economic impact, environmental justice considerations, product life cycle analysis, and legal implications and barriers. Given the promising economic indicators identified at this stage, the research team will evaluate these and other factors as the project progresses.

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