Rare earth elements – recovery from coal-based materials

Stephen Mills

The report considers the strategic importance and growing global demand for rare earth elements (REEs), vital components for many high-tech consumer devices and defence applications. They are also a crucial element of the energy transition and are used in renewable energy technologies such as solar panels, wind turbines, electrolysers, and electric vehicles.

Global reserves of REEs are currently estimated at around 130 Mt. Production has increased significantly during the past decade from just above 100 kt in 2013, to 350 kt in 2023, an upward trend that is expected to continue. REEs are mined predominantly in China, Vietnam, Brazil, Russia, India, Australia, and the USA, although several other countries have also identified reserves but are not yet in production. The global market for REEs was US$5.3 billion in 2021 and is projected to increase to US$9.6 billion by 2026.

The wind turbine market is expected to account for around 30% of the global growth in the use of rare earth (RE) magnets in the coming years.

China dominates global production and supply of REEs, which causes concerns over cost and security of supply, especially in western nations. China's position has allowed it to periodically flood or otherwise control global REE markets since the 1980s; REEs' supply and prices have been influenced by domestic tax policies, quota systems, and export restrictions. The country has also stockpiled critical materials during market gluts. China continues to tighten its grip on the mining and refining of REEs and international markets via the introduction of measures including further export restrictions and tighter control over state-owned companies. Against this background, many countries are attempting to develop their own sources and establish alternative supply chains as a matter of national security.

Alongside production from natural mineral sources, focus has increased on recovering REEs from other sources, primarily coal-based. Many studies have focused on REE recovery from different coal-based materials including hard coal and lignite, coal refuse, mine drainage, and coal combustion by-products such as fly ash. Many of these materials are readily available in large quantities. For example, large legacy dumps and stockpiles of fly ash are often present in countries with a history of coal power generation and/or industrial use. Significant amounts continue to be produced and stored each year. Some sources contain significant levels of REEs, hence their potential as an indigenous resource.

However, extraction from some materials such as fly ash can involve the use of aggressive reaction conditions that often include the use of strong acids, alkalis, and organic solvents. Multiple extraction stages are also likely to be required, needed to achieve acceptable recovery rates. In practice, several initial processing stages may be combined to ease downstream REE extraction. Thus, a combination of techniques may be applied.

A wide range of techniques for extracting REEs from coal-based materials have been proposed or trialled, such as physical beneficiation, acid leaching, ion-exchange leaching, bioleaching, thermal treatment, alkali treatment, solvent extraction, and more novel concepts. Fundamental research continues into recovery processes requiring less aggressive reaction conditions.

There may be advantages to extracting REEs from coal-based materials. For example, coal deposits are widespread and often more accessible than mineral deposits, making recovery easier and less expensive. Furthermore, as the coal is normally already being produced for energy purposes, the addition of REE recovery could generate an additional income stream. In other situations, REE recovery could be combined with environmental remediation measures, such as treatment of acid mine drainage, thereby reducing its impact on adjacent land and watercourses.

Coal geology and chemistry, chemical engineering, process development, and extractive metallurgy support the development of many of these possible extraction processes. Data generated by these combined efforts allow various REE recovery concepts to progress from feasibility studies to laboratoryand pilot-scale investigations, and several processes are moving towards initial commercial production.

This report examines the more established methods for extracting REEs from mineral ores and coal-based materials, reviews some of the more promising novel techniques being developed, and considers progress being made towards the possibility of the latter becoming feasible alternatives to conventional sources. Some promising recent advances and their potential for achieving commercial-scale operation have been reviewed, although most still require further development. Numerous recovery schemes have been proposed or trialled. However, many have only been evaluated at limited scale, and lack hard data on their economic viability and possible environmental impact. Some require further technical development and optimisation. Many need scaling up to validate their technical effectiveness and

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provide operational data needed for techno-economic, environmental impact, and life cycle analysis studies. These data will be needed for the successful development of economic and relatively environmentally benign REE recovery processes. With many REE recovery technologies still at early stages of development, current technoeconomic analyses are characterised by high degrees of uncertainty.

Recovering REEs from coal-based materials is an evolving field, although significant achievements have been made in recent years. However, for any recovery scheme to be considered viable, it will need to achieve the right balance between efficiency, cost, and environmental impact. Nevertheless, several promising pathways towards industrial-scale production are being pursued, and more fundamental research is continuing into recovery processes less reliant on harsh reaction conditions.

There is a big incentive to achieve viable REE recovery from coal-based materials – successful development would diversify sources, easing concerns over current and future market domination, and help global progress towards technologies effective in meeting the challenges of climate change.

Tab. 1. Top REE Producing Countries, 2023(Kelly, 2023).

Country	Reserves, Mt	Comments
China	44	World's leading producer – output of 210,000 t in 2022 In 2022, mining quotas were increased by 25% over 2021, the fifth consecutive increase In recent years, China has also imported heavy REEs from Myanmar
Vietnam	22	Only 400 t was produced in 2021, increased to 4300 t in 2022
Brazil	21	In 2022, Brazil only produced 80 t, a fall from 500 t in 2021 Major new developments are expected to boost output significantly
Russia	21	Russia produced 2600 t in 2022 Conflict in Ukraine may have affected plans to increase output
India	6.9	In 2022, production was 2900 t India has 35% of the world's beach and sand mineral deposits, significant sources of REEs
Australia	4.2	Australia's production was 18,000 t in 2022 Has the world's sixth-largest reserves New production capacity in development
USA	2.3	USA had second highest output in 2022 at 43,000 t Mining limited to California's Mountain Pass mine Alternative domestic sources being sought
Greenland	1.5	No production in 2023, but several major projects in development

Fig. 2. Rare earth prices 2021-24 (based on Pr-Nd oxide) (Dempsey, 2024).

What are REEs?

REEs comprise seventeen metallic elements: yttrium, scandium, and the fifteen lanthanides on the periodic table: lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium (Figure 1).

Despite their name, REEs are relatively plentiful in the Earth's crust; for example, cerium is the 25th most abundant element at 68 parts per million (ppm), similar to copper. However, because of their geochemical properties, REEs are usually dispersed and mixed with other mineral species which can make their recovery technically and economically challenging. Minerals containing REs are currently produced mainly in seven countries (Table 1). REEs generally occur in a range of minerals such as halides, carbonates, oxides, and phosphates, but not naturally as metallic elements. Carbonates and placer deposits are the leading sources of REE production. Placer deposits are a type of mineral deposit in which REE grains are mixed with sand deposited by a river or glacier.

Global reserves of REEs are currently estimated at around 130 Mt. Production has increased significantly during the past decade from just above 100 kt in 2013, to 300 kt in 2022, increasing further in 2023 to 350 kt. The top global producers by country are shown in Table 1.

Although recent global events such as the Covid pandemic caused prices of REEs to fall, they are again rising, a trend that is expected to continue as future demand (Figure 2).

The growing strategic importance of REEs is considered as economies across the world continue to develop and adapt to global pressures such as energy security and climate change. The conventional production of REEs from mineral sources is explored. This is followed by an examination of the presence of REEs in coals and coal-derived wastes, and the potential of these as viable, sustainable alternative sources of REEs.

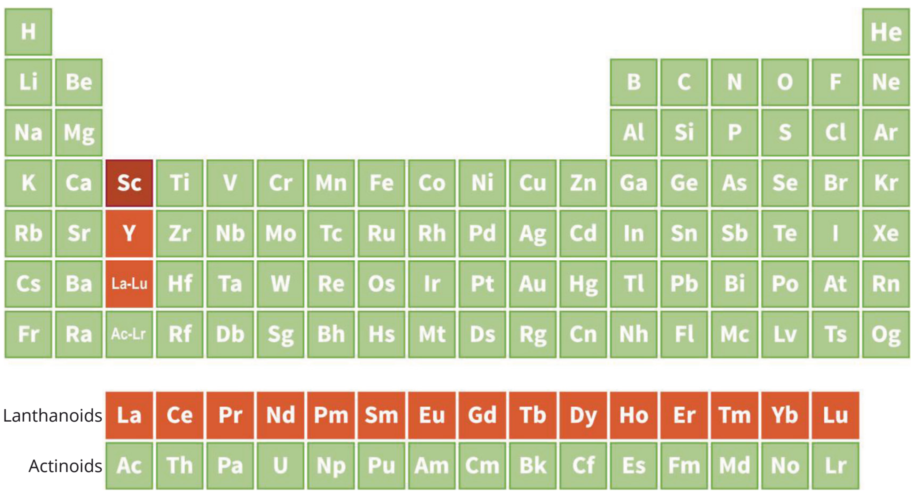

Fig. 1. Rare earth elements.

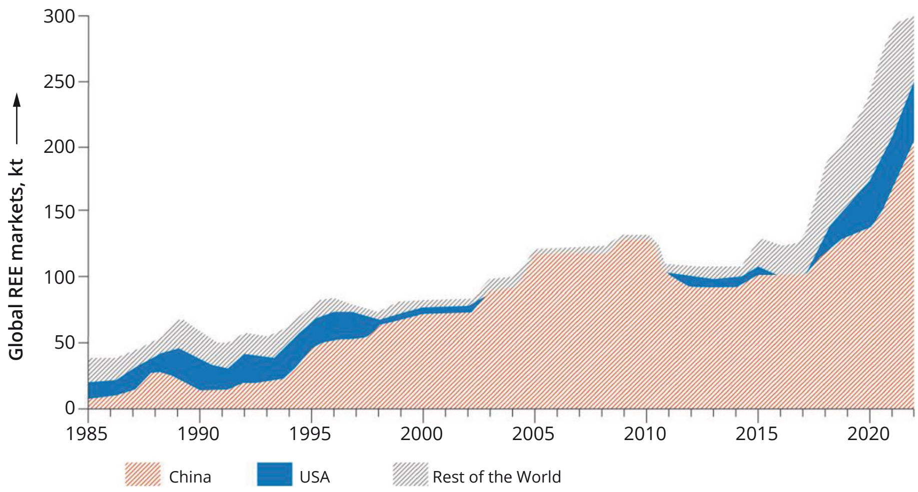

Fig. 3. China's dominance of global REE markets (Johnston and others, 2023; Dempsey, 2024).

The strategic importance of REEs

China's dominance of the global REE market continues to raise concerns over cost and security of supply, especially in western nations (Figure 3). For example, the EU is an important producer of wind turbines and motors for EVs. However, current European REE production is negligible at both the mining and processing levels.

China dominates the global production of magnets, although some economies are in the process of developing or boosting their own magnet manufacturing capacity. For example, in the USA, projects are underway for new production in South Carolina and Texas. A plant is being developed in Estonia and new facilities are also planned for several other parts of Europe. A major growth area is for permanent magnets, especially those incorporating neodymium, dysprosium, and praseodymium. Producing high-performance magnets is highly specialised with much of the world's production currently based in China. Japan produces some magnets, and Europe and the USA also have a very small production capacity.

China's dominance of REE production and supply has allowed it to periodically flood or otherwise control global REE markets since the 1980s; REE supply and prices have been influenced by domestic tax policies, quota systems, and export restrictions. The country has also stockpiled critical materials during market gluts. Thus, other countries are urgently seeking to develop alternative sources to China.

In October 2024, China's grip of the mining and refining of REEs and international markets was strengthened through the introduction of further export restrictions and tighter control over state-owned companies. The Chinese government made it more difficult for foreign companies to purchase REEs mined and refined in the country. Chinese exporters are now required to provide the authorities with detailed, step-by-step tracings of how shipments of REEs are to be used in Western supply chains, allowing greater control over their destination and end-use. China also began the process of taking greater corporate ownership over REE mining and production, acquiring the last two foreign-owned REE refineries in the country. Simultaneously, national security officials tightened the flow of information about REs – labelling RE mining and refining as state secrets.

Conventional REE mining

REEs are often intimately mixed with various types of rock, clays, and mineral sands and are usually produced from conventional opencast mines or via in situ leaching. The latter involves pumping a chemical solution into a body of ore to dissolve the targeted materials. The solution is then recovered and transferred to collection pools before further downstream processing to purify and separate the different REEs. As the various REEs exhibit similar chemical behaviour they are difficult and expensive to separate.

Three major sources of REEs are bastnasite, monazite, and xenotime. Once mined, such materials are usually crushed and milled into a finer form to ease recovery.

Commercial processing usually employs a solvent extraction process, likely to involve a chemical reaction that forces some of the elements present to change phases, such as from a liquid to a solid. When this happens, the elements separate, and their concentrations change. However, the change is relatively minor, hence it takes numerous extractions to reach a purified state. Even though the process is well established, it is inefficient, time-consuming, and generates considerable amounts of waste. Thus, the production chain can be lengthy and complex.

The final stage of REE production is further refining and segregation in a smelting facility to remove impurities and obtain individual elements, often in their pure REO form (Figure 4).

The presence of REEs in coal

Alongside developments targeting REE recovery from conventional mineral sources, interest has increased in the potential of alternative REE-containing sources such as coal and coal-derived materials, readily available in significant quantities in many parts of the world.

During the process of coal formation from peat to brown coal/lignite to bituminous coal, an evolutional change of modes of REE occurrence takes place. In the initial stage of peat formation, REEs occur mainly in mobile, water-soluble modes, with significant levels of REE compounds in organic complexes; mineral matter plays an insignificant role, even though RE minerals such as xenotime may be present. The organic mode of REE occurrence remains dominant at the brown coal/lignite stage. With a few exceptions, the role of minerals in the total balance of REEs generally remains minor. With more mature bituminous coals, the role of minerals increases significantly. Thus, in the process of coal metamorphism, the influence of organic modes gradually decreases up to the full transformation into mineral phases in anthracite and graphite.

Coals can be enriched with different trace elements and have the potential to be sources for both light and heavy REEs. REEs are

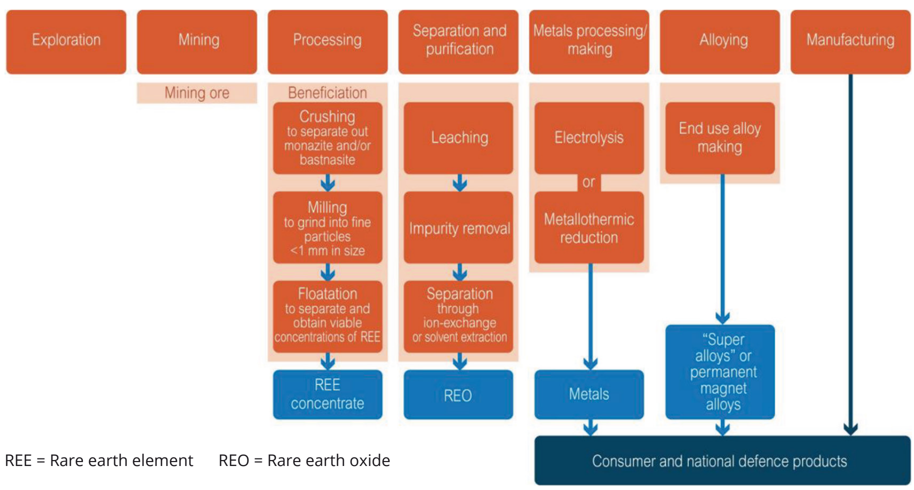

Fig. 4. Production stages for conventional REE recovery (USDOE, 2017).

mainly present in coal as phosphate minerals such as xenotime and monazite, as sedimentary minerals such as zircon, or as clay minerals including kaolinite and illite. In some low rank coals, 50-60 % of REEs are primarily associated with clay minerals present.

The global average REE content of lignite has been estimated to be around 69 ppm, and its associated ash 378 ppm. The average for bituminous coal is around 69 ppm, and its ash 469 ppm. Some studies suggest that about a quarter of the REEs in the feed coal are associated with organic matter, with relatively higher concentrations of HREEs. But although some coals contain significant amounts, as noted, levels can vary significantly.

It can be difficult for project developers to determine the levels of REEs present in various deposits. They have traditionally relied on laboratory analysis, which can be time-consuming and expensive. A novel technique has been developed by the Delft University of Technology in the Netherlands, using a portable Fourier-Transformed Infrared (FTIR) spectroscope to overcome this issue. Materials from German lignite mines at Profen and Schlenheein were evaluated, and modelling confirmed that FTIR could be a useful tool for quantitatively predicting REE contents with an acceptable level of accuracy. This will be important in selecting suitable sources, thereby avoiding the processing of materials which contain only low levels of REEs. However, some researchers agree that although portable methods may be useful for initial examinations, they may not be fully effective in all cases.

The search for these increasingly important materials has expanded in many countries, and some potential sources have been identified as being well above the USDOE cutoff level of 300 ppm. For example, on an ash basis, coals with high REE concentrations have included Appalachian coals in the USA (500-4000 ppm), Canadian coals in Nova Scotia (up to 483 ppm), and Russia (300-1000 ppm).

Interest in REE recovery from both bituminous coal and lignites is increasing. Lignites have a high humic acid content that can bind metal ions and REs to non-metals in a ring-like structure (chelation), which can make their recovery achievable under relatively mild conditions. Various projects are underway.

Some lignites contain more than 1000 ppm REEs, although most fall in the range of hundreds of ppm. The HREE/LREE ratio can exceed 2, which is higher than normal and makes them more attractive. Heavy REEs have been found predominantly in the organic fraction which has been attributed to the higher oxygen content of these immature coals.

REEs in coal wastes and by-products

Compared to conventional recovery of REEs from ores and other mineral sources, the use of coal-derived waste streams could provide several benefits:

- the need to open new mines is eliminated, avoiding associated environmental disruption. Also, mining costs may be negligible as it may be possible to recover REEs from existing washery operations;
- minimisation of leaching of toxic elements and their possible contamination of surface and ground waters from tailings ponds and dumps (Dodbiba and Fujita, 2023);
- wastes such as fly ash are often available in large quantities in countries with a history of coal use which reduces the need to mine virgin ore and creates a beneficial use for such wastes;
- some coal-related materials contain higher levels of HREEs and critical REEs relative to lighter variants;
- developing commercial processes to recover REEs from wastes could be relatively rapid. New mines can take many years to launch, while recovering REEs from wastes may take only four (Creamer, 2023). For example, a new REE mine planned for Europe's largest known deposit of REOs could take up to 15 years to become operational (Onstad, 2023);
- use of wastes can reduce environmental and occupational hazards associated with conventional REE extraction by avoiding environmentally hazardous processing techniques;
- recovery of REEs from legacy waste dumps could help reduce environmental impacts such as acid run-off and land erosion. This could be combined with coal recovery in some cases. REE extraction and/or coal recovery could generate an income stream used to remediate a particular site;
- REEs become concentrated in solid coal wastes such as fly ash, compared to the input coal, making processing easier and improving process economics;
- fly ash and some other wastes are already in the form of small particles, so mechanical reduction such as grinding or milling may be unnecessary (Hower and others, 2025);
- some forms such as AMD contain REEs that can be easily recovered; consequently, the associated carbon footprint is less than for a conventional mining and milling operation. Furthermore, the main by-product from AMD treatment is clean water suitable for release;
- securing REEs from wastes makes use of an indigenous resource, thereby reducing reliance on imported supplies and improving national energy security;
- the strong global interest in developing additional REE supplies creates an investment opportunity for commercial firms active in the global value chain; and
- some types of REE (especially heavier variants) in coals and coal wastes can be present in greater amounts than in conventional ore bodies meaning they can command a higher selling price.

Therefore, some coal wastes and by-products can be promising candidates for cost-effective REE recovery. However, despite these potential advantages, a major challenge for any commercial-scale recovery process will be the large volume of material that may need to be processed. Some US studies suggest that more than 2000 t of ash would need to be processed to obtain one tonne of product.

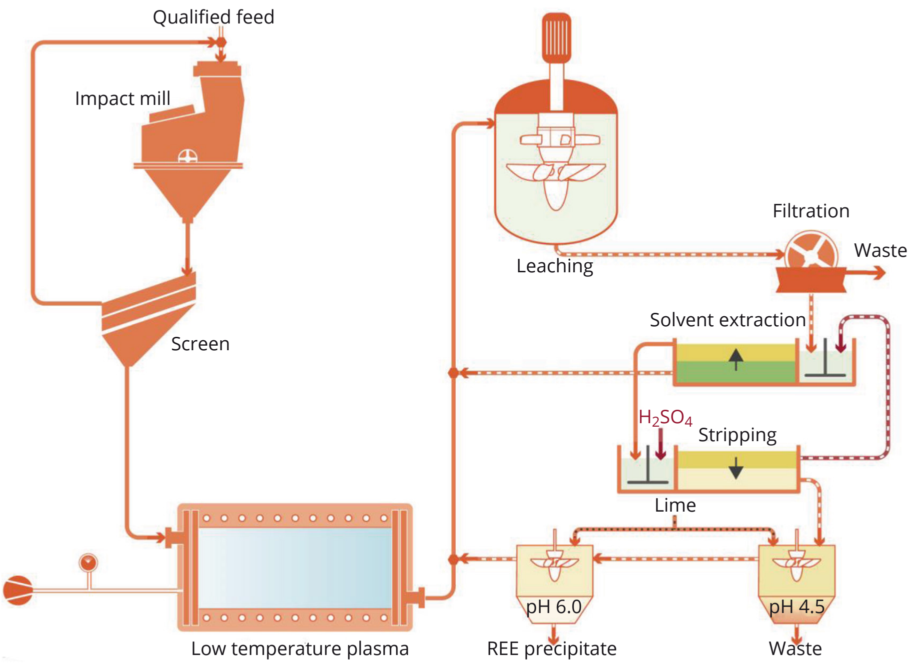

Fig. 5. Plasma assist technology (Green Car Congress, 2020).

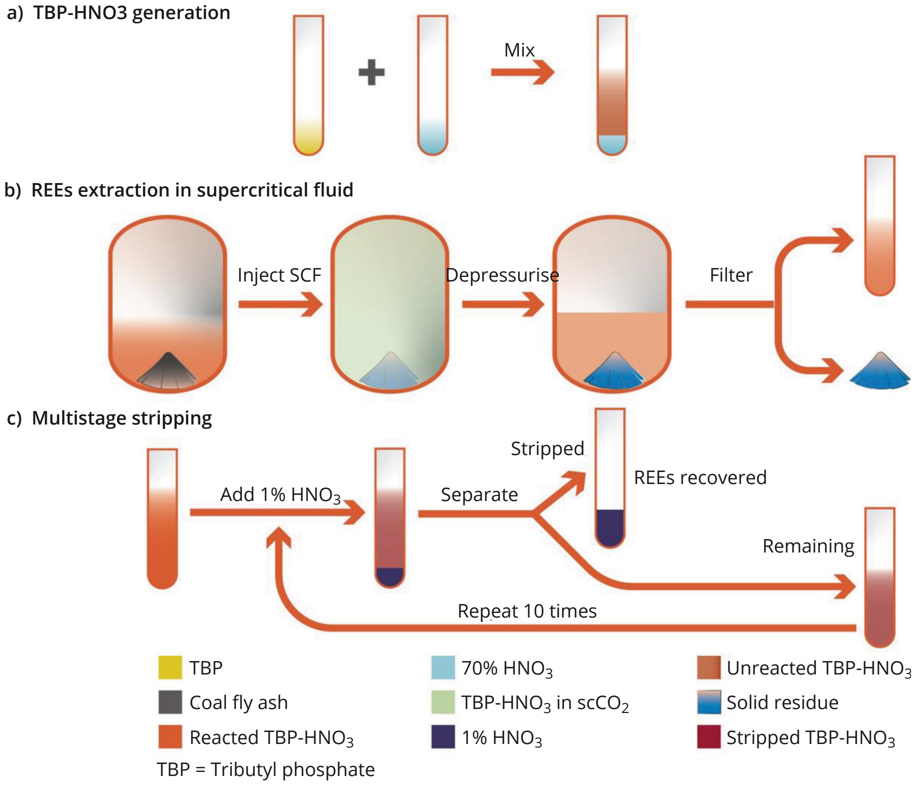

Fig. 6. REE recovery using supercritical fluids with tributyl phosphate (TBP) (Zhu and others, 2023).

Compared to conventional recovery of REEs from ores and other mineral sources, the use of coal-derived waste streams could provide various economic and environmental benefits. Often available in large quantities, they could become a useful resource, helping develop a secure indigenous supply chain, thereby reducing dependence on possibly unreliable imported supplies. However, despite these potential advantages, the extraction of REEs from coal wastes and other coal-derived by-products remains an emerging field. Many potential recovery processes have yet to be fully evaluated in terms of their overall economics, and their variable makeup can make this challenging. However, limited analysis suggests that the value of REEs in one tonne of coal ash could be around $250 (Shi and others, 2023). Numerous processes have been proposed during the past decade, some of which are progressing towards larger scale deployment, although none have yet reached this stage.

Techniques for REE recovery from coal wastes

Many techniques have been suggested for recovering REEs from various types of coal wastes and by-products. Extraction from some materials such as fly ash often involves the use of harsh reaction conditions and multiple stages, needed to achieve acceptable recovery rates. However, several initial processing stages may be combined to ease downstream REE extraction. Thus, a combination of techniques may be applied (examples: Figure 5 and Figure 6).

Acknowledgement

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Kurzfassung

Seltene Erden – Rückgewinnung aus kohlebasierten Materialien

Dieser Bericht befasst sich mit der strategischen Bedeutung und der wachsenden globalen Nachfrage nach Seltenerdelementen (SEE), die für viele High-Tech-Verbrauchsgeräte und Verteidigungsanwendungen unverzichtbar sind. Sie sind auch ein entscheidender Bestandteil der Energiewende und werden in Technologien für erneuerbare Energien wie Solarmodulen, Windturbinen, Elektrolyseuren und Elektrofahrzeugen eingesetzt.

Viele Studien haben sich auf die Rückgewinnung von Seltenerdmetallen aus verschiedenen kohlebezogenen Materialien konzentriert, darunter Steinkohle und Braunkohle, Kohleabfälle, Grubenwasser und Nebenprodukte der Kohleverbrennung wie Flugasche. Es wurde eine Vielzahl von Techniken zur Gewinnung von Seltenerdmetallen vorgeschlagen oder erprobt, wie z.B. physikalische Aufbereitung, Säurelaugung, Ionenaustauschlaugung, Biolaugung, thermische Behandlung, Alkalibehandlung, Lösungsmittelextraktion und neuere Konzepte.

Die Geologie und Chemie der Kohle, die chemische Verfahrenstechnik, die Prozessentwicklung und die Rohstoffgewinnung unterstützen die Entwicklung möglicher Extraktionsprozesse. Die durch diese gemeinsamen Anstrengungen generierten Daten ermöglichen es, verschiedene Konzepte zur Rückgewinnung von Seltenerdelementen von Machbarkeitsstudien zu Untersuchungen im Labor- und Pilotmaßstab weiterzuentwickeln. Mehrere Prozesse bewegen sich in Richtung einer ersten kommerziellen Produktion. Viele Prozesse wurden jedoch nur in begrenztem Umfang evaluiert und es fehlen konkrete Daten zu ihrer Wirtschaftlichkeit und möglichen Umweltauswirkungen. Einige erfordern eine weitere technische Entwicklung und Optimierung. Es wird weiterhin Grundlagenforschung zu Rückgewinnungsprozessen betrieben, die weniger auf aggressive Bedingungen angewiesen sind, die oft den Einsatz von starken Säuren, Laugen und organischen Lösungsmitteln beinhalten.

Die Rückgewinnung von Seltenerdmetallen aus kohlebasierten Materialien ist ein sich entwickelndes Feld. In den letzten zehn Jahren wurden bedeutende Erfolge erzielt, aber ihre Gewinnung bleibt eine Herausforderung. Damit ein Rückgewinnungssystem als tragfähig angesehen werden kann, muss es das richtige Gleichgewicht zwischen Effizienz, Kosten und Umweltauswirkungen finden. In diesem Bericht werden die etablierteren Methoden zur Gewinnung von Seltenerdmetallen aus kohlebasierten Materialien untersucht, einige der vielversprechenderen neu entwickelten Techniken werden überprüft und die Fortschritte auf dem Weg zu ihrer möglichen Umsetzung als praktikable Alternativen zu herkömmlichen Mineralerzen werden betrachtet.

Es besteht ein großer Anreiz, eine praktikable Gewinnung von Seltenerdmetallen aus kohlebasierten Materialien zu erreichen – eine erfolgreiche Entwicklung würde dazu beitragen, die Quellen zu diversifizieren, Bedenken hinsichtlich der aktuellen und zukünftigen Marktbeherrschung zu zerstreuen und Fortschritte bei Technologien zu erzielen, die den Klimawandel wirksam eindämmen.