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Salty Solutions: Tapping Geothermal Brines for Rare Earth Elements

Commentary by Emma Jones Fredrickson and Anna Littlefield

As ever changing policies strain trade relationships between the U.S. and China, rare earth elements (REEs) provide China with leverage in negotiations, adding renewed urgency to seek alternative, domestic sources of these high-value materials. REEs are essential to the development and manufacturing of electric vehicles, wind turbines, semiconductors, and defense technologies, and are integral to the transition to cleaner energy. However, their extraction is not low impact. REE mining is accompanied by environmental contamination risks and potential impacts to human health, necessitating new solutions for sustainable mining practices.

A promising strategy for sourcing REE’s is extraction from geothermal brines, which naturally contain these elements at low concentrations. This approach is gaining traction as geothermal energy experiences renewed policy and investment focus, especially under the current administration. Taking advantage of these overlaps through dual purpose project development has long-term economic benefits that could improve the U.S. ability to establish energy and mineral independence.

The REE Supply Dilemma

REEs are traditionally sourced from primary mining such as China's Bayan Obo mine, which is the largest REE mine in the world. The deposit is estimated to contain more than 100 million metric tonnes of REE reserves, accounting for over 40% of the world's known reserves and half of global production. In 2017, China controlled 95% of the global production market and approximately 78% of U.S. imports come from China. Deposits do exist outside of China in countries such as Vietnam, Russia, the U.S., and Brazil. Also rapidly gaining ground in the market are African mines which are projected to make up around 9% of the global supply in the next four years. The only active REE mine in the U.S. is the Mountain Pass mine in San Bernardino County, California which produced about 26,000 tonnes of rare earth concentrates in 2019.

Alternative sources for and methods of extracting REE's are being explored as a means to circumvent the environmental and health impacts of traditional mining extraction such as waste generation, water contamination, ecosystem destruction, and airborne pollution. Some alternative pathways to REE's include E-waste recycling, recovery from existing mine waste, deep-sea mining (a controversial topic), and extraction from geothermal brines. Here, we explore the latter as a promising option for lower impact REE recovery.

Geothermal Brines: What are they and why do they matter?

Geothermal brines are hot, mineral-rich fluids from deep beneath the Earth's surface. They can be found all over the world, but some examples include the Salton Sea Geothermal Field, The Geysers (California), and Cornwall (UK). Geothermal brines contain REEs, particularly light REEs (La, Ce, Nd), generally on the scale of parts per billion (ppb), as well as other critical minerals such as lithium, zinc, cobalt, and manganese.

At geothermal power plants, the fluids are pumped from below ground and converted to steam which is used to drive turbines and generate electricity. Hot fluid moves through a heat exchanger and the resulting cooled brine returned to the subsurface via injection well. This cooled geothermal brine from the plant discharge is the target for REE recovery. Recovery methods depend on high brine flow volumes associated with energy production to compensate for the relatively low concentrations.

How do you get REEs out of brines?

There are numerous engineering challenges to overcome in designing REE extraction methods from geothermal brines. First, high flow rates in geothermal plants require the method to be scalable without impeding flow. Low concentrations also necessitate that extraction methods are highly selective for targeted REEs, over more abundant ions such as Na^+, K^+, or Ca^{2+} in the saline solution. The salinity, temperature, and often extreme pH of geothermal fluids also pose a corrosion challenge to equipment in contract with the brine. Finally, each geothermal site has a unique fluid chemistry, requiring any extraction methods to be adaptable in order to be broadly applied.

Currently, several options exist for REE extraction from geothermal brines:

- **Adsorption and ion exchange** are relatively straightforward approaches that work by removing metal ions by passing cooled brines through solid, static, engineered materials. While this is a simple, and environmentally friendly option, forcing significant flow through solid-mediums can impede flow, causing pressure drops, and ultimately pumping power losses.
- **Solvent extraction** is another method employed at existing plants. Here, organic solvents are used to bind specific rare earths, so they can be removed and separated. The drawbacks of using organic, volatile solvents include the need for ecological mitigation as well as high energy costs.
- **Magnetic Nanoparticle Separation**, was developed by Pacific Northwest National Lab (PNNL). This method involves adding magnetic nanoparticles to still-flowing cooled brine. The particles capture the target REEs, are then removed with an electromagnet, and stripped of the REEs after which, the particles can be reused. The short residence time, reusability, scalability, and introduction method make this option sustainable and promising.

Early Success in Europium Extraction

In 2021, the PNNL team published a study on the Magnetic Nanofluid Method and an economic feasibility assessment of its use for recovering europium from geothermal brines. With improved REE selectivity they performed experiments to test the system performance under more realistic conditions. With a 90% recovery scenario, the adsorbent material used for the nanoparticles was determined to be fully reusable with a lifespan of 6,000 operating hours. A techno-economic analysis (TEA) was conducted to determine hypothetical capital and operating costs for this method. With an estimated total capital investment of $6.77 million, the internal rate of return (IRR) was estimated to be above the 15% target at, 18.1%. The IRR is most sensitive to the electromagnet cost, europium concentration, and market value of europium.

Although these economic estimates are encouraging, expenses used are theoretical, and the dependency on volatile markets, unique brine chemistry, and challenges associated with different extraction methods leaves significant uncertainty. Additional research is needed to inform these extraction methods' ability to scale and adapt to diverse operations. Some funds were allocated to this work in July, 2024 when the Department of Energy's (DOE) Geothermal Technologies Office (GTO) selected seven national laboratories to receive over $6 million in research funding for critical mineral characterization and recovery research in geothermal brines.

REE's are not the only target critical mineral elements with recovery potential from geothermal brines in research and development. Direct lithium extraction (DLE) includes methods designed to selectively remove lithium from brines as opposed to relying on conventional removal methods which require more land, water, and time. Adaptations of these technologies for use in geothermal applications are in pilot scale but show potential in terms of environmental friendliness and economic feasibility.

Why this matters for U.S. Policy

Strengthening our toolbox for safe, sustainable REE recovery methods is an important step towards energy system resilience and geopolitical independence. Developing domestic REE sources could improve US national defense capabilities and economic stability. Investing in the development and implementation of technologies like magnetic nanoparticle separation can also drive job creation in the clean energy sector while leveraging existing infrastructure. A 2023 world labor report predicts that labor demands in critical mineral recovery could double by 2030 and the World Resources Institute found that for every million dollars the U.S. invests in clean energy like geothermal, twice as many jobs are generated than would be for fossil fuels.

While the benefits are vast, there are still risks involved, as this is early stage emerging technology. As determined by the PNNL's TEA, the market price of REEs can significantly impact returns on investment, and the REE market is volatile. Additionally, federal support for these initiatives is needed in the form of grants, and subsidies, and while the white house has deemed domestic critical mineral and rare earth element sourcing a high priority, recent budget and tax proposals propose major cuts to DOE and energy research.

Supportive policies are needed to bolster the funding, development, and optimization of these technologies. This could include incorporating REE recovery in geothermal tax credits, incentivizing U.S.-based REE refinement, and investment in research and development, pilot programs, and existing GTO/DOE efforts.

Working Toward a Sustainable, Independent Future

Geothermal brines provide a unique opportunity to take advantage of existing infrastructure and apply environmentally friendly recovery methods for REEs and other critical minerals. With the right policy support, the U.S. can lead the charge to develop domestic supplies. Rare earth elements are integral to the clean energy transition, and perhaps geothermal energy could, in turn, hold the key to sourcing rare earths.

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Emma Jones Fredrickson is a graduate student in the Mines chemistry department finishing up her master's degree in geochemistry. Her research focuses on critical mineral characterization of Colorado mine drainages and associated microbiology. Emma joins the student researcher team for the summer as a former educator with 5 years of experience teaching secondary agriculture, food, natural resources, and science. Her academic background spans interdisciplinary fields with a B.S. in Geoscience from Southern New Hampshire University and a B.S. in Agricultural Education from Colorado State University. Emma is excited to be contributing to the dissemination of science topics that impact our world, communities, and future.

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Anna Littlefield is the Low Carbon Energy Technologies Program Manager for the Payne Institute at the Colorado School of Mines. As a current PhD student in the Mines geology department, her research focuses on the geochemical impacts of injecting CO2 into the subsurface as well as the overlap of geotechnical considerations with policymaking. Anna joins the Payne Institute with 8 years' experience in the oil and gas industry, where she worked development, appraisal, exploration, new ventures, and carbon sequestration projects. Her academic background is in hydrogeology with an M.S. in geology from Texas A&M University, and a B.S. in geology from Appalachian State University. Anna is passionate about addressing both the societal and technical challenges of future of energy and applying her experience to advance this effort.

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