TAPPING INDUSTRIAL WASTE STREAMS TO PROMOTE A CIRCULAR ECONOMY FOR RARE EARTH ELEMENTS

Dr. Alexa Schmitz – REEgen Inc.
Dr. Sean Medin – REEgen Inc.
Brooke Pian – REEgen Inc.
Kate Ivanovich – REEgen Inc.

Abstract

REEgen is building a clean, climate-smart system for bio-manufacturing rare earth elements (REE) and other critical metals using engineered, nature-based processes. We are focusing on recovering REE from secondary sources, such as recycled electronics and other post-consumer goods, to help fill the gap between supply and demand and to promote a circular economy. REE are important components for many modern technologies including electric cars, wind turbines, nickel-metal hydride batteries, and many types of fluorescent lighting. Despite their criticality, less than 1% of REE are recycled world-wide. Many efforts are underway to develop processes for recycling REE; however, logistical challenges, such as electronics disassembly, have made this effort slow-going. Instead, REEgen has been exploring recovery of REE from the by-products of existing metal recycling processes, including precious metal and steel recycling. In both industries, the reclaimed metal is smelted in furnaces for purification, and undesirable components go to the slag portion. Previous work identified steel slag as a potential end point for magnet-relevant REE in e-waste. At REEgen, we have also found that slag from recycling platinum group metals from catalytic converters (autocat) is even higher in REE – up to 3%, which is higher than some REE mines. At REEgen, we can recover the REE from these slags with high efficiency using REEgen's proprietary bioleaching system. In REE bioleaching, microbes convert sugars into a solution of organic acids, called a biolixiviant, that can be used to leach metals from a solid matrix. This process is based on natural mechanisms that have been optimized through genetic engineering. In contrast to harsh, concentrated acids currently used in this process such as sulfuric acid and nitric acid, REEgen's biolixiviant is non-hazardous and biodegradable. For many REE feedstocks, including metallurgical slags, bioleaching is competitive with leaching using 70% nitric acid, and the lack of hazardous wastewater production is attractive to our feedstock suppliers. With clean technologies for REE recovery, REEgen can more easily mine from these industrial waste streams at the source of production without generating hazardous waste or incurring unnecessary shipping costs. In doing so, REEgen can manufacture recycled, US-sourced rare earth materials at a competitive price, helping to close the gap between supply and demand and support the creation of a circular economy for these critical metals.

Introduction and Motivation

REEgen is building a clean, climate-smart system for extraction and purification of energy-relevant rare earth elements (REE) and other critical metals (CM) using engineered, nature-based processes. There are two key problems associated with the REE supply chain: 1) REE production is monopolized in China, and 2) the expected demand will outpace the current supply. China has produced as much as 95% of the global REE supply in the past couple of decades (1). Rare earth mining and conventional methods of REE processing cause extensive ecological damage, generate large volumes of hazardous waste, and have a substantial carbon footprint (2), and thus are infrequently performed in the U.S.

REE are important components for many modern technologies including electric cars, wind turbines, nickel-metal hydride batteries, and many types of fluorescent lighting (3). A single off-shore wind turbine can require more than a metric ton (MT) of REE, which results in production of a huge amount of hazardous waste gas, wastewater, radioactive waste, and CO_2-equivalent (4). The clean energy transition is increasing demand for REE, yet the reliance on other countries for these materials creates a vulnerable supply chain and national security risks. Despite their criticality, less than 1% of REE are recycled world-wide (5). Many efforts are underway to develop processes for recycling REE; however, logistical challenges, such as electronics disassembly, have made this effort slow-going. Instead REEgen has been exploring recovery of REE from the by-products of existing metal recycling processes, including precious metal and steel recycling. In both industries, the reclaimed metal is smelted in furnaces for purification, and undesirable components go to the slag portion. Previous work identified steel slag as a potential end point for magnet-relevant REE, such as neodymium (Nd) and praseodymium (Pr) in e-waste (6). Research has also indicated that REEs concentrate in copper slag (7), likely because copper is the end refining point for many secondary refiners of different

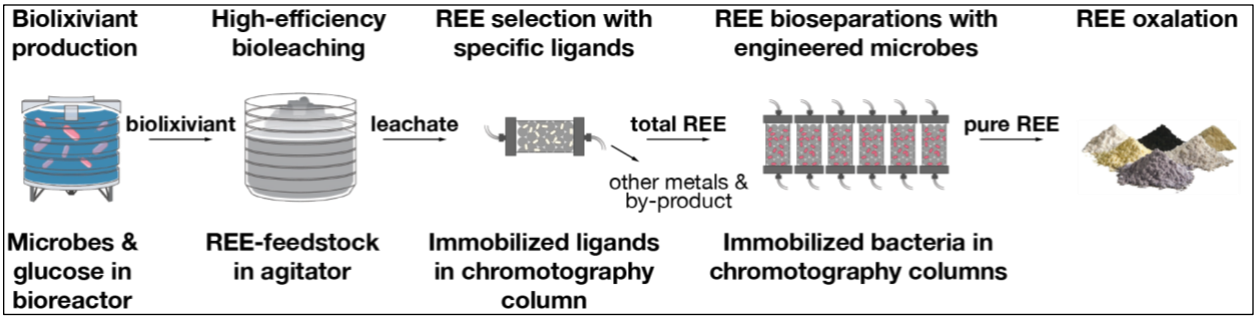

Figure 1: Schematic for REEgen's overall biorecovery process. *For bioleaching, microbes convert sugars into a solution of organic acids, called a biolixiviant, that leaches metals from solids. In REE-selection, we use REE-specific ligands to selectively concentrate total REE. In bio-separations we use bacteria engineered to adsorb specific REE better than others to separate the selected total REE ions with bacteria-packed chromatography columns. These processes are all based on natural mechanisms that have been optimized through genetic engineering.*

post-consumer goods that contain rare earth permanent magnets, such as medical devices. Through our own work presented here, we have found that slag from recycling platinum group metals from catalytic converters (autocat) is even higher in REE – up to 3%, which is higher than some REE mines – and at least 10% of that is the magnet relevant REE, Nd and Pr.

At REEgen, we are developing a REE and CM production technology that utilizes sustainable, waste-minimizing, economically-viable metal recovery processes (**Figure 1)**. Our overall REE production involves three key steps: bioleaching (8,9), REE-selection (10,11), and bioseparations (12,13). In this paper we present our work with REE bioleaching. Bioleaching of metals has been used by the mining industry for over a century, particularly for solubilization of copper, nickel, gold, and silver (14). Today microbes are used mainly for heap bioleaching of copper and stirred tank bio-oxidation of gold, contributing 15 and 5 percent of the world's copper and gold, respectively. More recently, the use of bioleaching for the recovery of other metals, such as REE, has been investigated but not yet commercially developed.

Bioleaching of REE is mediated through complexolysis and/or acidolysis by (in)organic acids produced by the microbes (15). The use of bacteria and fungi that produce organic acids is an attractive option for bioleaching non-traditional feedstocks due to the clean, biodegradable nature of the leaching solution. Several microbial species have been explored for their use in REE bioleaching (9), and researchers at the Idaho National Lab have even demonstrated commercial viability for the use of a wild type *Gluconobacter oxydans* for recovery of REE from secondary materials (16). However, improvements are still needed to bring the technology to market. At REEgen, we are genetically engineering REE bioleaching to improve efficiency, address commercialization hurdles, and tailor the process to various REE feedstocks.

Current State of Technology Industry Uses

Conventional methods for REE production are harmful to the environment. Currently, the production of Nd and Pr typically requires open-pit or underground mining methods. The ore is crushed, ground, and then beneficiated into a concentrate. REE concentrate is typically leached with strong acids such as sulfuric, nitric, or hydrochloric acid or is treated with a strong base like sodium hydroxide (4). Often this process is conducted at high temperature and pressure. After the REE are liberated from the minerals, they are precipitated, roasted into oxides, and sent to a REE separation facility where they are separated by passing REE through a series of stages of purification in solvent extraction batteries (3).

Mining REE is extremely energy and resource intensive: the carbon footprint of 1 kg of neodymium oxide ranges from 12 kg CO_2-Eq (17) to 66 kgCO_2-Eq (18). The metals manufacturing and the mining industry in general are responsible for 40% of all industrial greenhouse gas emissions, and 10% of the global energy consumption (19). For many common minerals, pre-concentration of REE can also result in unacceptably large concentrations of radioactive elements thorium and uranium, requiring additional processing to avoid environmental contamination. Strong acid leaching produces large amounts of waste that need to be neutralized and has a large carbon footprint, especially when high temperatures are required. Solvent extraction utilizes toxic solvents, and the solvent extraction process requires high temperatures and chemical inputs (3).

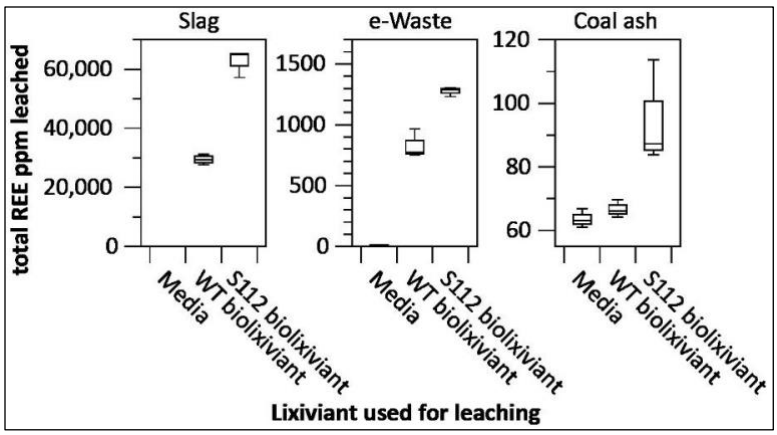

Figure 2: Comparison of REE leached with biolixiviant produced by the engineered strain (S112) vs. the wild type strain (WT). *Bacteria were grown in an Infors Minifors 2 bioreactor until saturation. Glucose was added to the culture, and the fermentation broth was harvested as a biolixiviant after 24 hours. Solids were milled to below 74 um. 100 mg of the powder was mixed with each leaching solution in a screw cap vial, and agitated on a multi-tube vortexer for 24 hours. Metals in the resulting leachate solution were measured by ICP-MS. n = 4.*

Technology Approach

REEgen is replacing the most environmentally harmful parts of the REE production process with cleaner, biological methods. Instead of using strong acids for leaching REE, REEgen uses a biogenic, biodegradeable leaching solution, called a biolixiviant produced by our engineered bacteria (*Gluconobacter oxydans)*. In this process, the microbes convert sugars into a solution of organic acids and other REE chelators that can leach metals from a solid mineral matrix (8,16,20,21). This process is based on natural mechanisms that have been optimized through genetic engineering. In the Barstow Lab at Cornell University, REEgen's co-founders created a whole-genome knockout collection for *G. oxydans*, which contains a deletion strain for every non-essential gene in the genome (22). Using this collection, we identified the comprehensive suite of genes contributing to REE bioleaching and targeted several of the greatest contributors to engineer a *Gluconobacter* strain (S112) with hyper acidification and greatly improved bioleaching efficiency (23).

Combined with process optimization at REEgen, these genetic engineering strategies have conferred over 2X improvement in REE bioleaching with the engineered strain versus the wild type strain when testing various feedstocks **(Figure 2)**. REEgen has connected with dozens of customers with industrial residuals, waste, or byproducts that contain elevated levels of rare earth elements. For many REE feedstocks, including metallurgical slags, bioleaching is competitive with leaching using 70% nitric acid, and the lack of hazardous wastewater production is attractive to our feedstock suppliers.

To date we have tested more than 20 different REE feedstocks using our engineered REE bioleaching strain and have investigated the commercially relevant parameters for identifying which feedstocks to target first. All have different parameters in terms of their availability, the value of the contained REE, the efficiency of our process for leaching those REE, and the ease of adoption for our potential suppliers and partners. As a result of this process, REEgen has begun focusing on recovering REE from metallurgical slags – particularly from those generated by autocatalyst smelters recycling platinum group metals (PGM) and steel mills with electric arc furnaces (EAF) that predominantly take in recycled steel. Not only are these slags typically landfilled, but the producers of the slag often pay a tipping fee to have it removed.

We have collected PGM slag from several PGM smelters across the United States, and steel slag from an electric arc mill in Upstate New York. We have found that both types of slags have economically relevant levels of REE, as well as other critical metals **(Table 1)**. Among the REE present, both types of slag have high levels of Nd and Pr – the magnet-relevant REE – and contain other metals that can be recovered and sold for additional revenue to help the economics. The total REE in the steel slag is around 0.03%, while the PGM slag contains over 3% total REE.

Table 1: Critical metals in slags (ppm)

Critical metals	Steel slag	PGM slag
†Neodymium	117	1980
†Praseodymium	34	831
†Dysprosium	4	--
Magnesium	49851	41400
Platinum	--	15
Aluminum	18846	145000
Silicon	unk	107000
Cobalt	11	17
Copper	257	14
Nickel	--	1270
†Yttrium	6	328
†Samarium	4	7.2
Vanadium	440	89
Strontium	328	1410
Palladium	unk	36
Zinc	310	1270
Titanium	unk	3010
Iron	41307	39200
Zirconium	unk	20791
† indicates REE		

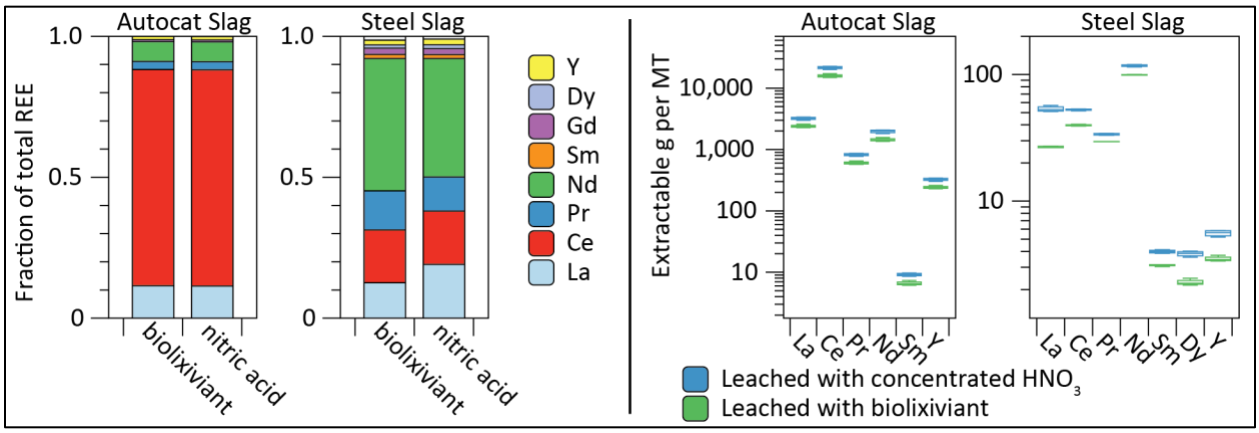

Figure 3: Left: *Breakdown of the different types of REE leached from two types of metallurgical slags. A comparison is shown for metals leached with S112 biolixiviant and 70% nitric acid. Autocat slag has a larger fraction of cerium compared to the other REE due to the use of ceria as a ceramic in the catalytic converter honeycomb. Steel slag has a larger fraction of neodymium relative to any other REE due to the presence of REE magnets that accompany the steel components of e-waste during magnetic separation* ***Right:*** *Extraction of the REE from the slags with REEgen's nonhazardous biolixiviant (from strain S112) is competitive with 70% nitric acid leaching. Also demonstrated is the very high level of REE in the autocat slag. Methods are same as for Figure 2.*

We have further tested the efficacy of our REE bioleaching system with the improved *G. oxydans* S112 strain on both slags **(Figure 3)**. Leaching with biolixiviant produced by S112 was compared with that of a 70% nitric acid solution. For the PGM slag, REE bioleaching with S112 was able to leach around 80% of all REE from the solids as compared with the nitric acid. For the steel slag, the S112 biolixiviant had a slightly lower comparable efficiency, but was able to leach the Nd and Pr with greater efficiency than the much less economical, and difficult to remove, lanthanum and cerium. This can be visualized in Figure 3a, which shows how the fraction of Nd and Pr among the total REE leached is larger for the biolixiviant than for nitric acid.

Discussion

Through our work testing various industrial residues and waste as potential REE feedstocks, REEgen has identified steel slag and PGM slag as key resources for creating a circular economy for REE. Nearly 20 million MT of slag is produced annually in the United States, including ferrous slag and smelter slag (5). Our testing results align with other studies that demonstrate that steel slag can have elevated levels of REE, especially the magnet-relevant Nd and Pr (6). In a typical rare earth ore, the most abundant REE are La and Ce, which are often difficult to remove from the more economically important REE, like Nd and Pr. In allanite ore from the Halleck Creek mine in Wyoming, USA, the total REE content is around 1% while the total NdPr content is about one quarter of that, and LaCe content is two thirds (24). In the case of steel slag, NdPr makes up over half of the total REE, while LaCe is only around one third. This skew in REE content can greatly help with the production of an NdPr oxide that might be sold directly into the permanent magnet value chain.

Unlike the steel slag, the PGM slag from autocat smelters has over 3% REE, which is already three times higher than the Halleck Creek mine in Wyoming, with the tremendous benefit that it does not need to be mined from the earth. While the NdPr concentration in the total REE is a bit lower (only 10%), this still constitutes a substantial amount of magnet-relevant REE that is otherwise being landfilled or buried in roads and building foundations. Through customer interviews and market research, we have learned that around 50,000 tons of autocat PGM slag is produced on a yearly basis, and all the slags we have tested have comparably high levels of REE. These slags are a tremendous untapped resource of magnet-relevant REE, and with clean, biological REE manufacturing processes, we can recover these critical metals with low energy inputs and environmental impacts.

The benefit of closing the loop in REE by recovering them from slag is the ability to immediately access these critical metals for their use today, instead of needing to disrupt value chains and business models of existing recycling industries, which would ultimately take years, if not decades, for adoption. One trade-off is the loss and dilution of REE throughout the upstream recycling processes, so parallel efforts are needed to identify other points in the value chain where these metals can be recovered with minimal loss or disruption. REEgen is working on these efforts as well, including the processing of magnetically separated steel scrap from recycled electronics, which has high

concentrations of rare earth magnets. Presumably this is also the reason we are finding such high levels of Nd and Pr in the steel slags, as these scraps are ultimately sold to the steel recycling mills.

For the success of REE recovery from slags, it will be crucial to minimize disruption to the slag supply and value chain and integrate the technology effectively within that chain. In 2023, the sale of US steel slags was estimated to be 16 million tons valued at about $900 million (5). These sales primarily were derived from the construction industry and the use of slag as a supplementary cementitious material (SCM). The copper smelting and refining industries in the US produce 2.5 million MT per year that can also be used as a SCM (25). Approximately 12 million MT of slag are used every year in the U.S. as SCM, which can reduce the carbon footprint of concrete while making it more durable (26). With REE recovery using bioleaching, the by-product of our leaching process still holds potential for use as a SCM. Preliminary data both published and from in-house research (data not shown) has demonstrated that this use is still possible for the solid residues that are left after the REE are leached (27).

Conclusions & Recommendations

The demand for REE is rising rapidly, with a compound annual growth rate of 12.6% (28). In particular, the demand for the magnet-relevant REE is driving this rise and is expected to quickly outpace supply. Finding alternative sources and closing the loop for these critical REE is not only important to alleviate the impacts of increased mining, but it is essential for developing the necessary infrastructure to combat climate change around the globe, as well as the defense technologies required to defend said infrastructure. Furthermore, finding alternative sources cannot wait for reverse logistics to be put in place to disassemble electronics, or for new mines to finish prospecting and obtain the necessary permits to begin commercial digging.

Slags from the existing metal recycling industries are an attractive and obtainable feedstock for the recovery of REE from post-consumer waste, such as rare earth magnets in electronics, or the rare earths in autocatalyst wash coats. Based on our surveys of numerous possible feedstocks, and the results of the work presented here, REEgen has developed a go-to-market strategy that begins by targeting the PGM slag as a high-value REE feedstock. The next target will include steel slag, but we must also develop a strategy to avoid disruption of existing markets for these slags. More work should be done to consider the applicability of these slags and the solid byproduct of REE leaching in concrete and other building materials. For many of these materials, the slags are not yet usable as SCM to replace ordinary Portland cement, so such work could even increase their viability and help offset even greater amounts of greenhouse gas emissions for the sustainable built environment – all while creating a circular economy for the rare earth element materials needed for advancing clean energy.

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About the Authors

Alexa Schmitz (Presenter, CEO, REEgen) holds a PhD from Cornell University, and first began developing bio-recovery of REE as a postdoctoral researcher in the Barstow Lab at Cornell. Her work developing a whole-genome knockout collection in *G. oxydans* that has set the basis for bioleaching improvements was published in Nature Communications in 2021. In May 2022, Schmitz was awarded an Activate Fellowship, which includes a research grant, two years of salary, and access to an extensive network of mentors, advisors, and investors.

Sean Medin (CTO, REEgen) holds a PhD in Biological and Environmental Engineering from Cornell University, where he worked alongside Schmitz while creating the foundational technology behind REEgen. His PhD work

primarily focused on developing bio-separations of REE in the Barstow and Wu labs.

Brooke Pian (VP Lab Research, REEgen) holds a BS in Environmental Engineering from Cornell University. Pian has over ten years of experience managing laboratory research, with six years being focused on the development of clean REE recovery systems alongside Schmitz and Medin in the Barstow Lab. She is a co-author and inventor on the core IP licensed by REEgen.

Kate Ivanovich (Scientist, REEgen) holds a BS in Biological Sciences from Cornell University. Ivanovich develops key protocols and experimental design to improve genetic enhancements and optimize REE bioleaching, is responsible for scaling up bioleaching systems and supports bio-selection efforts.