Title: *Upcycling Steel Residuals (Slags) for the passive purification of biogas*

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Research Objective(s): The research objective of this WEN-IR seed grant was to demonstrate through pilot-scale challenges, the process feasibility that low-value byproducts of steel manufacturing (slags), can be upcycled to significantly improve the quantity and quality of renewable natural gas (RNG) produced and recovered by anaerobic digesters and landfills.

This topic fits squarely in the WEN-IRT mission, because it focuses on improving direct energy recovery from wastewater, through a novel approach to biogas purification. As a sustainable alternative to large scale recovery of natural gas from landfills and sewage treatment plants, the (re)use of minerals that are discarded in large quantities by steel mills, may be engineered to reliably remove H_2S from biogas, with high efficiency. To date, these abundant residuals are commonly referred as "slags" and have only been (re)used as low-value geotechnical aggregates. Steel slags are composed of calcium, silica, magnesium, and iron oxides, including both amorphous and crystalline phases. This WEN-IRT seed project demonstrated that if properly prepared, certain steel slags are uniquely suited for biogas purification because they contain mineral surfaces that serve as potent sorption sites for purifying biogas generated during wastewater treatment, into commercial grade RNG. The novelty of the research proposed under this WEN-IRT work plan, manifest in a new approach for engineering slag surfaces for the specific purpose of biogas purification and RNG recovery; this establishes a synergist path for the beneficial reuse of slags in the next generation energy portfolio.

During the primary manufacture of iron and steel, slagging agents are added to strip impurities from the iron ore and scrap steel, which are fed to the steel furnaces. The impurities and slagging agents combine to form slags, which are tapped and disposed of separately from the high value structural metal. In 2017, US slag production was estimated in the range between 15 to 20 million tons and domestic slag sales amounted to approximately $350M USD. Slag is currently processed by about 25 companies worldwide, servicing active iron and steel milles, or otherwise reprocessing old slag piles.

Research Activities / Methodology: Proof-of-concept studies using common blast furnace slag confirmed the potential of this by-product to serve as a potent biogas scrubbing media in a pilot-scale demonstration at the Boulder Wastewater Treatment Plant. This study operated began in the late spring of 2018, and continued through the summer and fall semesters. The activity designed and operated single pass, plug-flow columns containing milled slag granules, which were continually challenged with actual anaerobic digester biogas.

Results: The most significant contaminant in biogas is hydrogen sulfide (H_2S), which must be removed in order to be used as a Renewable Natural Gas. If H_2S is not removed, it is oxidized to highly corrosive sulfuric acid during combustion, which destroys energy recovery infrastructure. The significant findings from this WEN-IRT seed study, confirmed that certain slag preparations can immobilize > 98% of influent H_2S, (with 1,000 ppm_v H_2S), and can retain as much as 0.02 kg H_2S per kg of slag media; this is much higher than existing specialty sorbents. This unoptimized feasibility study demonstrated that slag activated in this application can deliver engineering performance competitive with conventional scrubbing technologies, but is markedly cheaper. The results of this pilot-scale study warrant further investigation and now serve as the basis for Nicollette Laroco's PhD research in our EVEN program.

Accomplishments: Successful results from this pilot-scale study have opened a new sustainable materials research area, on the optimization of steel manufacturing byproducts for the successful upgrade of biogas to natural gas. These preliminary studies have proven this relatively valueless material can be used as a commercial grade sorbent for one of the most problematic and common biogas contaminants—in a passive scrubbing scenario. Results from this work earned the Innovative Technology Research Award at the 2018 Rocky Mountain Water Environment Association (RMWEA) Joint Annual Conference.

These results from this seed grant have since been leveraged into the following proposals (thus far): one to this year's Fulbright competition; the other, to an industrial sponsor (Pheonix Services, LLC) that sells raw steel slags for bulk commercial purposes. The Fulbright application has been successfully selected by the US Fulbright committee and forwarded to the host country (Spain). As of April 1, the industrial sponsor (Phoenix Services, LLC) has since been acquired by a Capital Management firm (Apollo Ventures) and the new ownership team is reviewing the proposal.

Conclusions/Next Steps: Steel slags are generated in large quantities around the world and generally considered low-value market for geotechnical fills or pavements. There are large stockpiles of this material growing on every continent except Antarctica. These results suggest slag can be cost-effectively upcycled for higher value in new wastewater treatment applications that are specifically focused on nutrient management (S) and energy recovery. This approach can likely have immediate impact in the biogas recovery industry, such that it can be easily scaled in a "plug and play" scenario with current gas treatment infrastructure. Future research will answer to one of the most common questions with respect to this application: Can this approach also be impactful in different countries, given different slag sources? In new sustainability contexts we will demonstrate the application of this technology across international contexts. The potential application for leveraging slags for nutrient sequestration and energy recovery from digesters in developing communities, will be explored in the immediate future. In this context, this PI will approach funding agencies that forward appropriate technology for scaling and demonstration monies (e.g. OAS, the World Bank) in this context of sustainable renewable energy.