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April 3, 2023

Reice Haase, Deputy Director
North Dakota Industrial Commission
State Capitol – 14th floor
600 East Boulevard Avenue, Dept. 405
Bismarck, ND 58505-0840

Subject: "Assessment of Lignite-Based Industrial Residues for Value-Added Product Creation through CO_2 Mineralization," Proposal to the Lignite Research, Development and Marketing Program by Dr. Johannes van der Watt, Principal Investigator

Dear Mr. Haase:

On behalf of the University of North Dakota, I am pleased to submit Dr. Johannes van der Watt's proposal on "Assessment of Lignite-Based Industrial Residues for Value-Added Product Creation through CO_2 Mineralization," for consideration by the NDIC's Lignite Research, Development and Marketing Program. Dr. Van der Watt is a Research Assistant Professor in UND's College of Engineering and Mines and is the Principal Investigator for this project. Dr. Van der Watt is proposing a two-year project with a total requested amount from NDIC of $250,000. The NDIC funding is being requested as a match to the DOE portion of the project, which is currently in the process of being awarded for $1,000,000. The total value of the overall project would thus be $1,250,000. We anticipate a start date in approximately July 2023.

Please contact Dr. Van der Watt with any technical questions about the project at (701) 777-5177 or johannes.vanderwatt@und.edu. If the NDIC selects this proposal for an award, please send any award documents and related communications to Sherry Zeman at sherry.zeman@und.edu for processing on behalf of UND. The $100 application fee is being handled as an electronic payment by UND and should reach your office in a timely manner. Thank you very much for your consideration of this proposal.

Sincerely yours,

Karen Katrinak

Karen Katrinak, Ph.D.
Proposal Development Officer, Research & Sponsored Program Development
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ASSESSMENT OF LIGNITE-BASED INDUSTRIAL RESIDUES FOR VALUE-ADDED PRODUCT CREATION THROUGH CO_2 MINERALIZATION

Total Project Cost: $1,250,000

NDIC Funding Request: $250,000

Date of Application: April 3, 2023

Principal Investigator:

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UND UNIVERSITY OF NORTH DAKOTA

COLLEGE OF ENGINEERING & MINES

TABLE OF CONTENTS

ABSTRACT

Objective: The University of North Dakota (UND) College of Engineering & Mines (CEM) and Envergex LLC are proposing to assess the techno-economic feasibility of using carbon dioxide mineralization (CO2M) as an enabling pathway to beneficiation of ashes and dry sulfur scrubber residues produced at lignite-fired power plants that, today, represent both economic and environmental liabilities for the plant owners. This work will be part of a larger Department of Energy funded project (DE-FE0032244) that will be performing a resource assessment of industrial wastes for CO2M combined with beneficial uses.

The project will specifically target the beneficiation of materials that are today not sold for cement replacement and will develop and test process schemes with potential to cost-effectively make these ashes suitable for concrete applications, all while also capturing and permanently sequestering a fraction of the plant's CO_2 emissions. CO2M has the potential to open new economic pathways to address key challenges such as high levels of soluble alkalis, calcium sulfite content and unburned carbon content.

To achieve the goal of developing new cost-effective pathways to beneficiating lignite-based ashes, we will: **1)** identify lignite-based ashes that have alkaline or other CO_2-reactive content and prioritize those that are present in significant volumes and/or represent large liabilities for the plant owner(s), **2)** perform a rigorous analytical characterization of the selected materials to determine their chemical composition and morphology to inform development of process schemes for CO2M and pre- and post-processing, **3)** perform a comprehensive laboratory-scale experimental evaluation involving CO2M testing, product characterization and application performance verification, and **4)** perform a high-level techno-economic assessment and carbon lifecycle analysis for selected materials and process schemes.

Expected Results: The project will identify materials types, their locations and quantities and develop feasible process schemes for CO2M and creation of value-added products. This will lead to significant waste elimination for the lignite industry, new revenue sources, and contribution to the environmental sustainability of cement/building products industry.

Duration: 24 months (tentative start date July 2023). **Participants:** UND CEM and Envergex LLC

Total Project Cost: $1,250,000 ($250,000 requested from NDIC and $1,000,000 awarded by U.S. DOE)

PROJECT SUMMARY

The University of North Dakota (UND) College of Engineering & Mines (CEM) and Envergex LLC are proposing to assess the techno-economic feasibility of using carbon dioxide mineralization (CO2M) as an enabling pathway to beneficiation of ashes and dry sulfur scrubber residues produced at lignite-fired power plants that, today, represent both economic and environmental liabilities for the plant owners.

This work is part of a new award from the United States (U.S.) Department of Energy (DOE) (DE-FE0032244) that focuses on a broader range of industrial residues/wastes for the purpose of evaluating the resource potential for CO2M and the ability to use CO2M to reduce waste and/or create new products. The broader DOE project will include evaluation of several industrial wastes, including lignite ashes/residues, recycled concrete, cement kiln dust, iron and steel slag, copper slag, and biomass wastes. For the lignite industry focus, the project will specifically target the beneficiation of materials that are today not sold for cement replacement and will develop and test process schemes that have the potential to cost-effectively make these ashes suitable for concrete applications, all while also capturing and permanently sequestering a fraction of the plant's CO_2 emissions.

The biggest factors contributing to the low quality of ashes from lignite combustion are unacceptable high levels of unburnt carbon and soluble alkalis. SO_3 content, particularly for dry scrubber ashes, could also be a challenge. The excessive accumulation of unburnt carbon in fly ash can result in several issues, including reduced strength, longer setting time, and decreased workability of the concrete. Additionally, excessive amounts of soluble alkalis in concrete can lead to abnormal expansion and cracking of the concrete.

Figure 1 outlines the innovative technology pathway we are proposing to upgrade lignite ashes. By using a combination of mild processing and accelerated CO2M technologies to eliminate impurities and alter the ash morphology and mineralogy, we can create an additional source of revenue for plant owners from ashes that are currently being disposed onsite. Fly ash, dry scrubber ash and mixtures of these with sorbents used for boiler ash deposit mitigation[1] (described in more detail later), represent the feedstocks for the upgrading process. Our mild processing removes unburnt carbon and soluble alkalis in the residues in

a first step which is then either succeeded or preceded by a CO2M process that captures/sequesters CO_2 emissions from the plants' flue gas or from the pure CO_2 stream generated by plants that implement large-scale CO_2 capture in the future. High SO_3 content can be addressed through physical separations/blending and during the CO2M process through transformations of the sulfite/sulfate phases.

In combination with the mild processing, the above-identified accelerated CO2M reactions between the ashes and CO_2 permanently sequester the CO_2 in mineral form and transform the ashes into highly sought after supplementary cementitious materials adhering to strict American Society for Testing and Materials (ASTM) requirements for class C/F fly ash. The upgraded residues composition is also suitable for use in valuable Limestone Calcined Clay Cement (LC^3), a low-carbon, mainstream general-use cement in the global cement market. This two-step upgrade approach (Figure 1) is specifically tailored to North Dakota utilities burning lignite coal and their unique operating configurations.

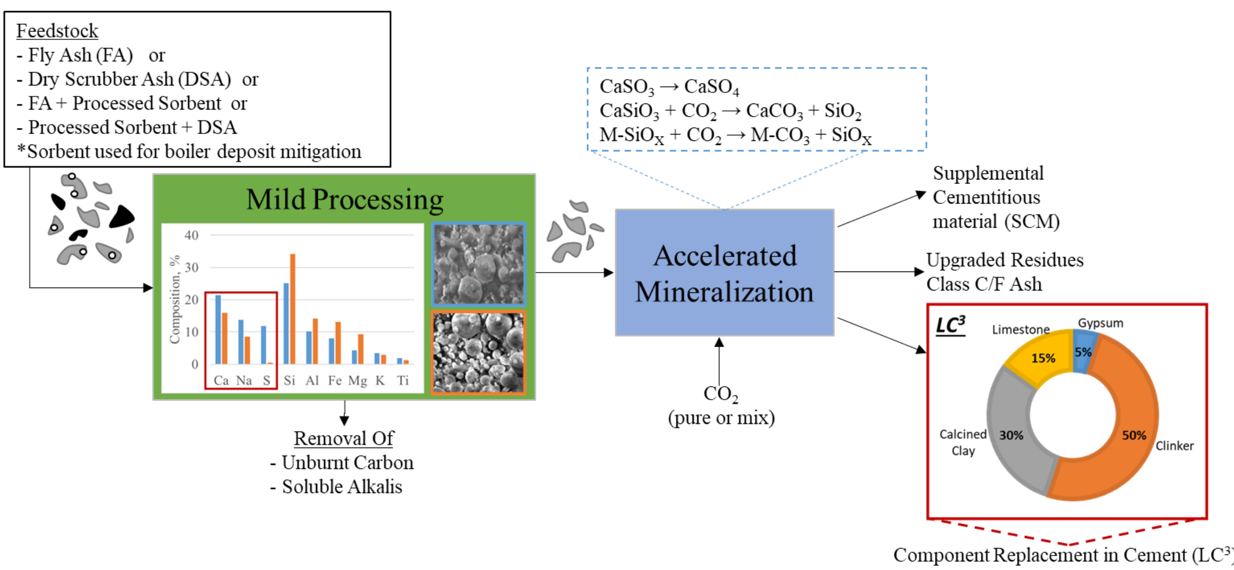


Figure 1: CO2M for cost-effective ash beneficiation.

<u>In addition to the primary benefit of beneficiating ashes for valuable use as cement replacement (and potentially other products), there are other benefits to be realized, described below:</u>

- **Reducing CO_2 emissions**: Ongoing testing of our team's novel CO2M technology has indicated that 100 grams of a typical ash containing suitable alkaline materials can sequester up to 18 grams of CO_2

(18wt% CO_2 capture capacity). For example, according to Otter Tail Power Company (OTP) (see attached letter of support in Appendix B), the Coyote Station typically produces about 100,000 tons/year of dry scrubber ash that needs to be disposed. While only representing a small fraction of the total Coyote CO_2 emissions (~3.5 million tons/year), our testing indicates that we could sequester about 18,000 tons/year of Coyote's CO_2 using CO2M with their dry scrubber ash. **We note:** we recognize that the value proposition of CO_2 emissions reductions at this scale is not large. The value this project brings is in leveraging the CO2M process and the resulting physicochemical changes to the ashes (and any carbon benefits, i.e. tax credits or offsets) to enable ash beneficiation that would not otherwise be cost-effective.

- **Waste reduction**: Most lignite power plants in North Dakota (ND) today are forced to landfill their ash residues onsite, representing both an economic and environmental liability. As a striking example of this liability, the EPA recently indicated that North Dakota's largest power plant, Coal Creek Station, may be facing the possibility of a multi-year outage to meet requirements under the EPA's coal combustion residuals regulation.[2] As depicted in Figure 1, our approach has the potential to address lignite ash beneficial use challenges. Our goal is to eliminate or drastically reduce the amount of newly landfilled ash, with the possibility of also enabling reclaiming of already landfilled ashes. Ash landfill reclaiming is not the focus of this project, but it will be evaluated at a cursory level.

In order to achieve the overall objective of cost-effective beneficiation of lignite combustion residues for use in existing commercial applications (i.e., concrete), we propose a series of **four technical tasks**:

1) We will identify lignite-based ashes that have alkaline or other CO_2-reactive content and prioritize those that are present in significant volumes and/or represent large liabilities for the plant owner(s). This will involve obtaining multiple <u>samples of lignite-derived ashes from Ottertail Power Company, Minnkota Power Cooperative, and Basin Electric Power Cooperative (see attached letters of support in Appendix B).</u>

2) We will perform a rigorous analytical characterization of the selected materials to determine their chemical and physical characteristics to inform development of process schemes for CO2M and pre- and post-processing. Based on the literature, our knowledge and prior related work, we have already identified tested processes that will be examined in greater detail. This task will enhance the available information to more exhaustively determine the possibilities.

3) We will perform a comprehensive laboratory-scale experimental evaluation involving CO2M testing with and without pre- and post-processing, as well as product characterization and application performance verification. This will involve using our team's accelerated direct CO2M approach (see Appendix A: Confidential Information) to perform screening tests for each of the selected ashes. We will then evaluate the physical and chemical properties of the resulting mineralized products and conduct performance tests for those materials that may be applicable to certain commercial end uses, such as in concrete.

4) We will perform a high-level techno-economic assessment (TEA) and carbon lifecycle analysis (LCA) for selected materials and process schemes. This will involve integrating all task findings to determine the system and process requirements and estimated costs for a full-scale beneficiation process. This will help us to determine the feasibility of our approach and will guide future scale-up.

PROJECT DESCRIPTION

Background

***Transition to a circular economy*:** The concept of circular economy has gained traction as a way to minimize waste and pollution by promoting the reuse and recycling of materials, and it is increasingly important for industries to find innovative ways to utilize their waste streams, such as the industrial residues generated by coal-fired power plants.

In recent years, there has been an increasing interest in the use of industrial residues for CO2M, which not only reduces greenhouse gas emissions but also creates value from waste materials. Lignite coal ash and dry sulfur scrubber residues are two potential feedstocks for CO2M as they contain metal oxides and metal silicates that can react with CO_2 to form stable carbonate phases, thus offering a promising solution for reducing carbon emissions and moving towards a more circular economy. However, the use of these materials for CO_2 capture at power plants is ignored since the generated residues can only capture a small fraction of the CO_2 emitted by the power plants. Therefore, on its own, CO2M application at coal plants is unlikely to be a complete solution.

Coal fly ash is known for improving the durability and workability of concrete mixes. It is used as partial cement replacement if its composition adheres to strict standards such as those reported by the American Society for Testing and Materials (ASTM) C618 for Class C and F fly ash.[3] Fly ash that does not conform to the ASTM C618 standards, typically due to impurities such as soluble alkalis, unburnt carbon, or semi-dry and dry flue gas desulfurization impurities, is typically disposed of in onsite ash ponds or landfills. This is a concern due to the increasing costs of ash storage and landfilling, as well as the potential for contamination of surface waters caused by leaking ash ponds.[4]

Furthermore, the American supply of fly ash has rebounded from a low in 2020, but its supply, specifically for use in concrete, remains constrained due to coal plant closures and movement towards other fuels.[5] This highlights the need to develop fly ash and dry scrubber ash beneficiation technologies to help keep up with this demand and better utilize the currently unused ashes.

Within North Dakota, we are aware of Basin Electric Power Cooperative's Leland Olds Station and Rainbow Energy Center's Coal Creek Station that provide fly ash for the construction industry. However, other power plants have to dispose of their ashes. Plants with ashes suitable for concrete applications have a significant economic advantage over those that do not. Our goal is to develop a technology pathway to make beneficiation of unsuitable ashes economic by leveraging the CO2M process.

Growing need for CO_2 capture: The push to reduce carbon emissions and combat climate change has led to an increased focus on carbon capture technologies for power plants that combust fossil fuels. With competition from renewable energy sources, these facilities must find ways to stay viable while reducing their carbon footprint.

However, one important consideration is the need to operate these coal-fired power plants at high capacity factors to repay the capital investment in carbon capture technology that relies on the 45Q tax credit. Previously, power plants had the flexibility to operate at lower loads, allowing for the removal of ash deposits from within the boiler at the "cooler" operating temperature. However, with the need to operate at high capacity factors, this operating flexibility is diminished, leading to increased ash fouling. This is particularly challenging in places like North Dakota, where high alkali-content lignite is combusted. Low rank coals contain significant amounts of sodium (Na) and potassium (K) which lower the ash melting point and can lead to the formation of sticky deposits on heat transfer surfaces.

One of the ways to overcome this challenge is by removing the vapor-phase alkali components in the flue gas by sorbents, as shown by Nguyen *et al.* (2022)[1], as part of a Department of Energy Project to mitigate the formation of alkali-induced aerosols at Minnkota Power Cooperative's Milton R. Young Station. The results from the full-scale demonstration showed the efficacy of the approach (i.e. injecting sorbent to capture vapor phase alkali species) and the added sorbent mixed in with the fly ash could be beneficial for use as partial cement replacement. Specifically, the combination of the fly ash and the sorbents that would be collected in the plant's particulate control devices, have properties that are desirable in LC^3 cements (see Figure 1).

***Challenges of using lignite ashes for cement*:** We consider two general categories of lignite ashes in this proposal: 1) fly ash and 2) dry scrubber ash.

Fly ash: To use fly ash as a partial cement replacement, it must adhere to the standards set forth in ASTM C618. As mentioned previously, the high alkali content in low rank coals such as lignite means utilities employ various strategies to use the coal effectively. For example, Minnkota Power Cooperative's Milton R. Young Station uses a cyclone-fired boiler. Cyclone-fired boilers burn coal at high combustion temperatures (~1650°C) and exhibit relatively high, but quite variable, fly ash unburnt carbon levels.[6] The unburnt carbon levels increase the ash's loss on ignition value, which is required to be below 6% as per ASTM C618.

Compared to cyclone-fired systems, pulverized coal fired systems generally have lower levels of unburnt carbon content in the ash. This is because the coal fed into the boiler is finer in size, which facilitates combustion that is more complete.

In addition, the combustion of coals with high alkali levels creates a unique challenge including elemental partitioning (most significant in high-temperature cyclone furnaces), with volatilization of the alkali compounds (Na and K) as demonstrated by Benson *et al.* (2014)[7]. Some of the vaporized alkali condenses (heterogeneously or homogeneously) as soluble alkali sulfates and are known to "coat" the fly ash resulting in relatively high alkali sulfate concentrations. High-alkali fly ashes (> 5% Na_2O equivalent) are not recommended for use with reactive aggregates for concrete mixes[8], making it unsuitable for concrete applications. Combined, these two criteria (unburned carbon and soluble alkali content) represent major challenges for the use of fly ash in concrete for plants with cyclone boilers.

Dry scrubber ash: Coyote Station (Otter Tail Power) and Antelope Valley Station (Basin Electric Power Cooperative) both have boilers that use a dry SO_2 scrubber and fabric filter for SO_2 capture and particulate control. A dry scrubber injects a slurry of hydrated lime, which reacts with the SO_2 to form a solid phase. The *partially* sulfated lime (mixture of uncreated lime, calcium sulfite and calcium sulfate) then mixes with the fly ash and is separated in the fabric filter. This mixture of solid particulate is referred to as dry scrubber ash.

The inherent concern with using dry scrubber ash as cement replacement is related to the same issues of unburnt carbon (if using cyclone-fired boiler) and high levels of soluble alkalis in the fly ash since it can contain 70%-85%[9] fly ash by weight. What makes dry scrubber ash also challenging is the presence of approximately 15%[9] hannebachite ($CaSO_3.0.5H_2O$) and 9% gypsum ($CaSO_4$).[13] Together, these contribute to the overall SO_3 content in the ashes. As per ASTM C618 for Class F/C fly ash, the SO_3 content cannot be greater than 5%. This restriction is in place to prevent hydration and durability issues during curing caused by the delayed formation of ettringite.[10] Compared to gypsum, hannebachite also exhibits greater stability in terms of reactivity and could therefore cause even more issues during curing when using dry scrubber ash in concrete. As such, dry scrubber ashes frequently get disposed of on the power plant's premises or in landfills.[11]

<u>Ash beneficiation and CO2M state-of-the-art technologies</u>**:** We provide a brief review of the relevant background on ash beneficiation and CO2M in the following sections.

<u>Ash Beneficiation:</u> No commercial method is known for mitigating high alkali sulfates beyond fly ash blending[12]. Blending is only applicable when a suitable low alkali-fly ash is available. This limits applicability of this solution. Our technology proposes a novel method for separating the alkali/sulfate/sulfite content from fly ash by exploiting the the fact that SO_3-rich phases precipitate during a different stage of the combustion process than the formation of fly ash particles.[4,13] This occurrence provides us the opportunity to separate alkali/sulfate/sulfite components from the fly ash.

For high unburned carbon (LOI) in fly ash, several commercial solutions exist.

- ***Triboelectric Separation[14]:*** This is an effective electrostatic-based technology for beneficiating a wide variety of fly ashes with high LOI (> 30%). The cost of separation is estimated at \$4-\$7 per ton fly ash[15]. However, the associated maintenance and operating costs are also high due to erosion of the conveyor components originating from the highly abrasive fly ash. Even though this process is considered the best for carbon removal for fly ash, lignite-based fly ash exhibits LOI values closer to about 10%[9].
- ***Thermal Processes:*** Burning the carbon represents the simplest form of carbon removal. This process is best suited for high LOI fly-ash (> 7%) to ensure self-sustaining combustion, but is expensive compared to the other processes (estimates of \$10-\$20 per ton of fly ash[16]).
- ***Classification:*** Mechanical and pneumatic classification are commonly used methods that can be employed to remove coarse particles from fine particles but are most effective as a pre-processing step, due to their low efficiency for sub-45µm sized particles. They are relatively inexpensive (\$1-\$3 per ton fly ash).[12]

CO2M: Mineralization brings unique changes to materials, such as the release of nanoscale silicate minerals and extremely fine limestone. Not only does this process capture CO_2, but it generates materials that are highly suitable as cement replacements and additives. For example, the fine limestone released via this process can be used to combat the deleterious effects of hannebachite and gypsum as noted previously since it coats these particles and accelerates hydration reactions.[13] CO2M is therefore an extremely powerful ash beneficiation technology. Current state-of-the-art technologies for CO2M relate to either in-situ or ex-situ technique.

- **In-situ mineralization**: In this technique, CO_2 is injected into underground reservoirs to promote reaction between CO_2 and minerals present in the geological formation to form carbonates. This technique is not relevant to the proposed application and is not discussed further.
- **Ex-situ mineralization:** Ex-situ refers to processes where the carbonation reaction occurs above ground, within a separate reactor or industrial process.[17,18] Ex-situ CO2M costs using CaO-and MgO-rich industrial wastes have been estimated at $70-$140 per ton of captured CO_2 based on the waste type, state and processing requirements. [18,19] <u>The CO_2 mineralization costs can be offset by the sale of the beneficiated materials and this is precisely what we aim to achieve in this project.</u>

Ex-situ CO2M can be subdivided into *direct* carbonation and *indirect* carbonation. Direct carbonation can be achieved by mineralization in aqueous solutions or gas-solid reactions, whereas indirect CO2M routes require the use of extraction agents such as acids and salts. According to Veetil & Hitch (2020)[17], ex-situ aqueous mineral carbonation represents one of the most promising and viable options for carbon capture and storage at the small-to-medium industrial scale.

While most CO2M reactions are thermodynamically favorable, they do exhibit significant kinetic and mass transfer limitations, making their overall reaction rates slow. An example of current ex-situ CO2M technology available in the U.S. is from Blue Planet Systems. Blue Planet Systems manufactures "Upcycled Aggregate", a by-product of demolished and recycled concrete that the company exposes to a calcium extraction process and then uses in concrete mix. The "Upcycled Aggregate" offers significant benefit compared to virgin aggregate in terms of strength and carbon footprint.[20] The process uses CO_2 and an aqueous capture medium such as ammonia, resulting in a CO_2 sequestered product and an aqueous ammonium salt. The aqueous ammonium salt is then treated with an alkaline waste product to regenerate the capture ammonia.[21] The main drawback to this technology is it requires energy intensive recovery of the solvent.

Carbon To Stone[22] is a new entrant into CO2M and proposes to directly capture CO_2 from air using regenerable solvents. This indirect ex-situ process would also likely require a costly solvent regeneration process that the company claims can be fulfilled by using heat or pressure changes from the process. The mineralization reactions are exothermic and this heat integration approach could prove extremely beneficial in the future.

Although state-of-the-art technologies for CO2M offer great potential, using solvents such as ammonia and the resulting ammonium salts can be corrosive and require recycling, complicating the process and making it challenging to implement on a large scale. Therefore, a simple process that can circumvent the use and recovery of solvents is necessary to achieve similar results in CO_2 removal and upgraded waste quality while being easily implementable on a large scale. In addition, such a technology would enable companies to adopt CO2M more easily, particularly in remote regions with limited access to large quantities of solvents.

Accelerated CO2M for cost-effective ash beneficiation: The proposed project will involve the use of our team's novel accelerated direct ex-situ CO2M technology, which is currently being demonstrated at lab-scale in a USDA funded project led by Envergex (USDA-NIFA-SBIR-008541)[23]. Our technology drastically increases carbonation reaction rates, through use of a novel contacting system and low-cost and benign additives. In addition to the ultra-fast reaction rates (high CO_2 loadings in a matter of a few minutes or less under optimized conditions), our technology's unique contacting design brings about morphology changes and the release of fine reactive silica and limestone in the reaction products, making them extremely valuable as cement replacement. Additional details can be found in Appendix A: Confidential Information.

<u>Summary of the Background and Key Research Problems to be Addressed:</u> As discussed in the previous sections, the proposed project combines mild ash processing and CO2M to achieve cost-effective ash beneficiation, targeting cement replacement application. Our project will address the following key research problems to achieve this objective:

- Lignite ash disposal represents significant costs and real environmental liabilities for plant owners. We are targeting a circular approach, whereby ash can be beneficially used, reducing/eliminating disposal costs, creating new revenue streams, and contributing to the sustainability of the construction industry.
- Our approach can beneficially integrate with alkali ash fouling control strategies that may become necessary as lignite plants adopt large-scale CO_2 capture systems (i.e., Project Tundra), such as through sorbent injection that has been successfully demonstrated at full scale at Milton R. Young Station.
- While some lignite plants already sell a portion of their ash for concrete applications, there are some plants whose ash contains certain impurities (LOI, alkali, SO_3) that make them unsuitable for these applications. Our approach leverages the physicochemical changes that occur through CO2M (along with any potential carbon reduction benefits) to open up new economic pathways for ash beneficiation/processing.
- To make CO2M reaction rates feasible for ex-situ CO_2 capture, novel technologies are needed. These are often complex and/or require expensive solvents and regeneration techniques. Our team is developing a novel CO2M technology that combines simplicity, ultra-fast reactions, and reaction product mineralogy and morphology that is beneficial for concrete applications.

Methodology

We propose to use two mild processing steps to lower the LOI and alkali sulfate content in the lignite ashes to levels suitable for use in concrete. The CO2M step is intended to capture CO_2, form stable carbonate species, alter the ash mineralogy and morphology (i.e., increase particle surface area), and liberate fine reactive silica. This extremely fine silica is a pozzolanic material that is typically used in industry to enhance the strength of concrete. The CO2M process is also known to be able to transform calcium sulfites (hannebachite) into soluble bicarbonate and bisulfite salts.[4] This allows an additional step whereby the sulfur content in dry scrubber ash can be reduced/tailored for easier blending with cement. Ultimately, the mild processing and accelerated CO2M steps are applicable to both fly ash and dry scrubber ash, with final blending of the upgraded scrubber ash with upgraded fly ash providing the last step in conforming to the maximum allowable SO_3 content of 5.0% in class C/F fly ash as per ASTM C618.

Additional details of our full approach are provided in Appendix A: Confidential Information. However, the following sections provide a brief description of the mild processing and accelerated CO2M based on the literature and our prior and ongoing work.

LOI reduction step: A simple physical separation step can be used to separate high LOI ash from low LOI ash, as shown in Figure 2. In this example, we were able to segregate fly ash from the Milton R. Young Station into fractions with LOI of <1wt% and >30wt%.

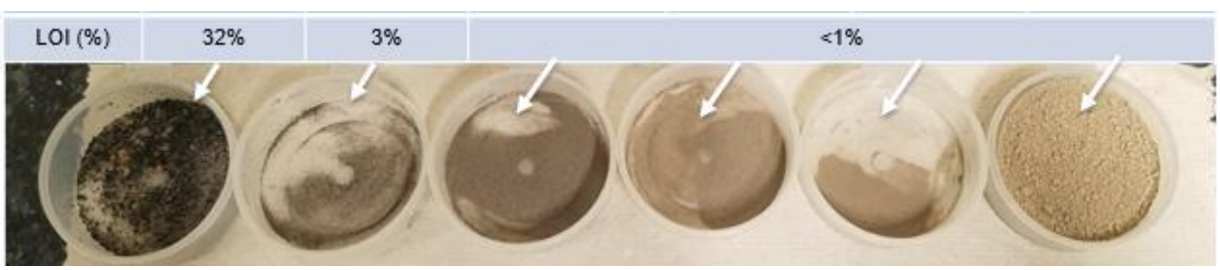
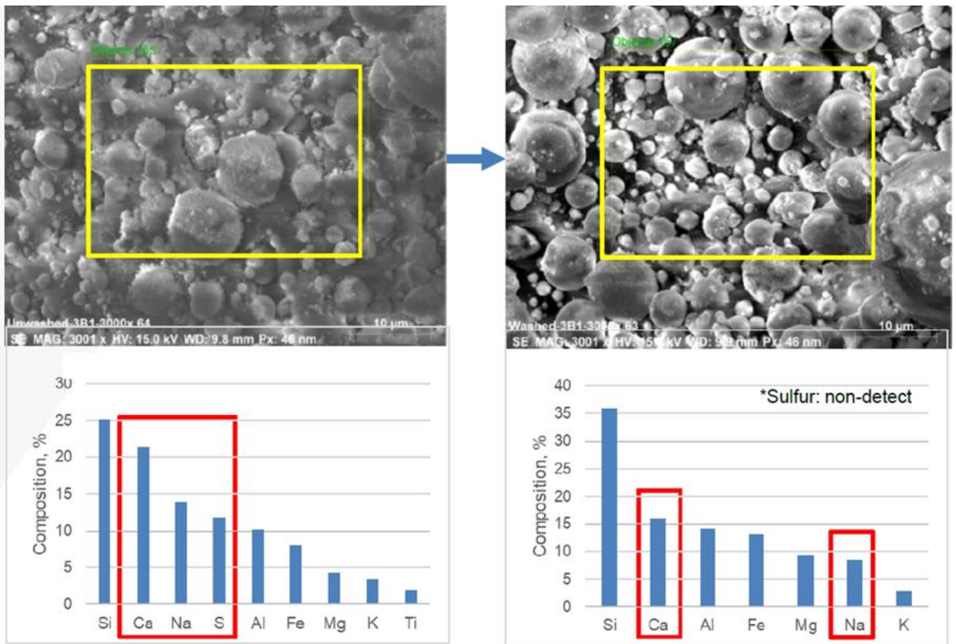


Figure 2: Ash partitioning into high LOI (>30%) and low LOI (<1%) contents.

Alkali reduction step: The effect of a second mild processing step is given in Figure 3, which shows the changes in the Na, S and K content before (a) and after (b) processing. It is clear that the processing reduced the Na and K content by about 40% and 30% respectively. The S removal was effectively 100% since no S was detected in the post-processed sample. The scanning electron microscopy images in Figure 3 show the morphological changes to the fly ash before (a) and after (b) the mild processing step. The mild processing step removed contaminants from the fly ash as the spherical nature of the fly ash is clearly visible in the post-processed material.



(a) Pre-processed (b) Post-processed

Figure 3: SEM-EDS results before and after mild processing of lignite derived fly ash samples.

Accelerated CO2M step: Envergex and UND have developed an innovative method for direct CO2M, which eliminates the additional expenses and complications associated with indirect routes. Figure 4 displays the performance of our CO2M technique on dry scrubber ash provided by Otter Tail Power, showing a significant improvement in CO_2 loading over baseline methods from just under 2wt% to nearly 18wt% CO_2 in the ash post mineralization.

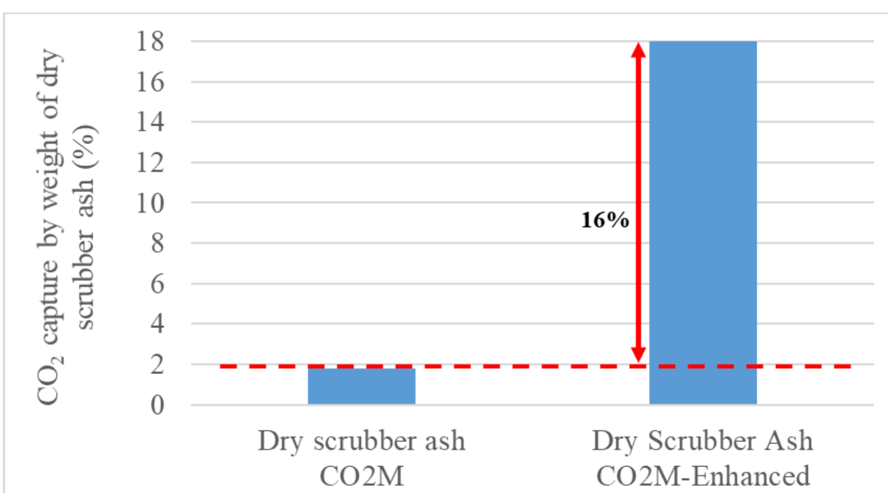


Figure 4: CO_2 loading on dry scrubber ash (Otter Tail Power) for baseline CO2M (left) vs. our accelerated CO2M technology (right).

This result, coupled with the existing 45Q tax credit, means that the residue could generate over $15 per tonne of dry scrubber ash through mineralization alone. However, the true value lies in the mineralogical and morphology transformations the material undergoes, as well as the added beneficiation that enables it to meet the suitable ASTM 618 requirements for use in concrete. Considering the current cost of cement at $130 per tonne, there is a clear demand and value for products that can partially replace cement in concrete.

***Tasks to be Completed**:* We propose five tasks that integrate with the larger DOE program and focus in our descriptions below on the specific activities related to evaluating the lignite-related resources.

Task 1.0 – Project Management and Planning

UND will manage and direct the project in accordance with the Project Management Plan to meet all technical, schedule and budget objectives and requirements in combination with DE-FE0032244. In addition, the purpose of this task is coordination and planning of the project with the other stakeholders, including the NDIC technical advisor and the DOE program manager. UND will lead this task with support from Envergex to address all items related to monitoring and control of project scope, cost, and schedule. UND will compile quarterly technical reports, topical reports, participate in meetings and make presentations at conferences as required.

Task 2.0 – Characterization of Coal-Combustion Residues

Detailed characterizations will be performed to define all relevant properties of the materials that will be required to develop processing schemes. We will specifically evaluate materials within the context of understanding their properties related to amenability to CO2M and why the materials may or may not be suitable for concrete applications today.

Subtask 2.1 – Sample Procurement

We have received support letters (see Appendix B) from Minnkota, Otter Tail and Basin Electric who will provide representative samples of ashes (fly ash, bottom ash, dry scrubber ash) from their lignite-fired power plants. We will work with these entities to collect 3-4 samples of each material type from each facility that are representative of the typical or most common operating modes for the plants (incoming coal quality, plant load, time before the next cleaning outage, etc.). We also have access to samples of fly ash mixed with alkali control sorbent from our team's prior commercial demonstration of alkali vapor capture at the Milton R. Young Station.[1]

Subtask 2.2 – Sample Characterization

The focus of this task is on determining properties that will impact CO2M process performance and/or required process conditions and why and to what extent each selected material is currently unsuitable for cement replacement by comparing it to relevant ASTM standards.

We will use multiple characterization methods following ASTM standards where appropriate: loss on ignition, bulk ash composition (XRF), minor and trace elements composition (ICP-OES), particle size distribution (sieving and Malvern analysis), morphology and chemical composition (SEM-EDS, including computer controlled SEM) and grindability (milling).

Within the context of evaluating the suitability for CO2M, a theoretical CO_2 uptake formula will be used to rank materials and the ranking value will be used to express conversion efficiency after mineralization experiments in Task 3.

Subtask 2.3 – Process Scheme Development

Based on the analyses results for promising ash materials, we will develop process schemes incorporating CO2M and any pre- and/or post-processing required to generate salable products. The techniques discussed in the confidential section of this proposal, Appendix A, will be utilized for these purposes.

Task 3.0 – Experimental Evaluation

We will perform a rigorous experimental evaluation of selected ash materials following the process schemes developed in Subtask 2.3 and following the process methodologies we described previously in Figure 1 and in more detail in Appendix A: Confidential Information. This task will be done in parallel with Task 4 to facilitate an iterative approach, where the product characterization results (Task 4) will inform the experimental test plan (Task 3) to generate optimized process schemes and conditions.

The lab-scale CO2M testing will utilize a mineralization process and test setup that has been developed from a separate project (USDA-NIFA-SBIR-008541). A representative sample from each of the selected industrial residues will be subjected to semi-batch testing – solids in batches with a continuous flow of reacting gases. The key performance metric will be CO_2 uptake, which will be evaluated as a function of pressure, operating temperature, H_2O/dry residue ratio, exposure duration, and CO_2 concentration. CO_2 concentrations typical of combustion flue gas will be evaluated in addition to higher concentrations or pure CO_2. We will measure the CO_2 uptake by determining the post-mineralization sample weight gain in combination with analytical techniques (total inorganic carbon analyzer).

Experimental evaluation of the ash processing steps (LOI reduction and alkali/sulfur reduction) will also be performed in this task via an iterative approach between CO2M testing and the Task 4 product characterization. More details of our processing methodologies are provided in Appendix A: Confidential Information.

Task 4.0 – Mineralized Product Characterization and Evaluation

To provide a quantification of the benefits of the proposed approach, we will perform analyses to compare the mineralized products to relevant ASTM standards to determine suitability for cement replacement. We will also use select ASTM tests to determine the performance of the resulting materials and further refine how they can be modified to meet the necessary requirements. The information obtained from Task 4 will be used to assist with the high-level techno-economic assessment (TEA) and carbon lifecycle analysis (LCA) in Task 5.

Subtask 4.1 – Reaction Product Characterization

We will assess the chemical composition, mineralogy, and microstructure of the reacted residues and compare the data to the unreacted/unprocessed materials. In addition, the mineralized materials will be assessed for toxicity/leachability and appropriateness for use as construction materials or landfilling.

Subtask 4.2 – Product Performance Testing

Cementitious material properties will be used for concrete mix design. The optimum content of the cementitious material (products generated in Task 3) will be determined using compressive strength as the criterion as compared to the control (cement-based concrete). The effect of optimum content on the fresh properties (slump, air content, unit weight), mechanical properties (compressive, flexural, tensile, and modulus of elasticity), and durability of concrete (freeze-thaw, air void content of hardened concrete, Rapid Chloride Ion Penetration, etc.) will be determined and compared to the control. At least three specimens will be tested for each property for statistical analysis purposes. Air void content of fresh concrete using Super Air Meter will be compared to the air void content of hardened concrete using Linear Traverse. Table 1 shows concrete properties, curing periods, ASTM standards, and major equipment for concrete testing.

Table 1: Concrete properties, ASTM standards, and equipment for concrete testing.

Property		Curing Period (days)	ASTM Standard	Equipment
Fresh Properties	Slump	0	C143	Slump content
	Unit weight		C138	Super Air Meter
	Air content		C231	
Mechanical Properties	Compressive strength	7, 28, 56, 90	C39	Universal Testing Machine
	Flexural strength		C78	
	Tensile strength		C496	
	Modulus of elasticity		C469	
Durability	Freeze-thaw Resistance		C1202	Rapid Freeze-thaw Cabinet
	Chloride penetration		C666	Rapid chloride penetration
	Air content		C457	Linear Traverse

Task 5.0 – Techno-Economic Assessment

This task combines the project findings into a feasibility study to identify and cost the viable usage pathways for the lignite coal ashes.

<u>Subtask 5.1 – Develop Alternative-Processing Schemes</u>

Results from Tasks 2-4 will be used to develop conceptual residue processing schemes applied at commercial scale. Process modeling (Aspen Plus) will be used in conjunction with experimental testing results from previous tasks to simulate commercial performance and mass and energy balances.

Subtask 5.2 – Develop Process Flow Diagrams (PFDs)

The simulations will be converted to preliminary PFDs incorporating mass and energy balances, equipment lists/sizing, and utility requirements.

Subtask 5.3 – Technical and Economic Analysis

The PFDs will be used to conduct a high-level TEA (i.e., Class V – Concept Screening, according to the Association for the Advancement of Cost Engineering (AACE) International) of the processes for comparison to each other and evaluation of their overall economic merit. Capital and operating cost factors will be used to estimate the economic viability of evaluated processes. This work will provide key information for future resource utilization decisions and will identify key targets to focus on and address scale-up considerations.

Subtask 5.4 – CO_2 Lifecycle Assessment (LCA)

The LCA will follow ISO 14040-14044 to establish a cradle to grave LCA for process schemes identified as viable. The LCA will evaluate the effects of using carbon dioxide from the facilities and using the processed materials for cement replacement or additives, or safer landfilling. The LCA will be broken up into three stages: **1)** industrial residue generation, **2)** processing and generation of mineralized residues, and **3)** sale and use or disposal of mineralized residues. This work will be coupled with TEA results to show tradeoffs between material processing targets and techno-economic feasibility. The LCA will be performed using the SimaPro 7.2 software. Inventory data from the GREET model will be prioritized; if data is not available the EcoInvent Database will be used.

Anticipated Results

The proposed project will deliver a comprehensive understanding of the economic and environmental benefits of lignite coal ash beneficiation through robust analytical and experimental evaluation of new pathways enabled by CO2M. The combination of detailed analytical characterization, experimental testing, LCA, and TEA will provide stakeholders with a complete picture of the costs and benefits of the proposed approach. This will enable stakeholders to evaluate the economic and environmental impacts of using

CO2M as a method for reducing waste disposal burdens on utilities and maximizing the reuse of coal wastes in the construction industry. We will generate results that are both broadly applicable to the ND lignite industry and specific to each of the individual lignite plants who are participating in this program.

Facilities and Resources

UND CEM houses the Advanced Materials Characterization Laboratory[24], which has all of the analytical equipment needed for the characterization efforts in Tasks 2 and 4. UND CEM also has experimental research facilities that will be available for the project, including the existing CO2M experimental test system and the concrete mixing, curing and evaluation testing facilities. Other facilities available to the proposed project include process simulators; UND has several relevant resources, including ASPEN Plus® and HSC Chemistry, that will respectively be used for establishing heat and mass balances for use in the TEA, and chemical equilibrium calculations to compare the theoretical conversion of chemicals to the experimental results.

Techniques to Be Used, Their Availability and Capability

This information was provided previously in the Methodology section in the description of the tasks to be performed. All of the techniques to be used have been well established in our previous technology development, via the use of various ASTM standards, and in previous successful projects involving similar subject matter.

Environmental and Economic Impacts while Project is Underway

No environmental or economic impacts are anticipated during project execution.

Ultimate Technological and Economic Impacts

We recognize that utilities and researchers have worked for many years on beneficial ash utilization and that many ND lignite plants today are still landfilling their ash. The key advancement/differentiator that our project brings is the leveraging of the CO2M process. We aim to demonstrate that CO2M opens up new economic pathways to ash beneficiation that would not otherwise be possible.

The ultimate technological and economic impacts of this project are significant. The project promotes the economical, efficient, and clean use of lignite combustion residues by creating a circular economy within North Dakota, where coal-derived residues are seen as a valuable resource that can be recycled in a sustainable and environmentally friendly manner. This project can create new job opportunities and ensure economic stability and opportunity in the lignite industry. It can also contribute to the effective marketing of lignite and the by-products associated with it by demonstrating the development of marketable products with a high probability of near-term commercialization.

As the EPA and environmental groups mount additional pressure on utilities relating to coal ash disposal and the construction industry demands more and more high-quality coal ash for cement replacement, it is clear the economic benefits that could be realized if our approach is successful: 1) reduced or eliminated landfilling and its associated environmental and economic liabilities, 2) new significant revenue streams for the power plants, and 3) additional volume of coal ash to offset manufacturing of fresh Portland cement and improved sustainability of the construction industry.

Why the Project is Needed

Coal ash is a large current liability for coal plants, as strikingly evidenced in the recent news about the potential multi-year outage Coal Creek Station might be facing. The project is needed because it offers a sustainable and environmentally friendly solution for the management of coal ashes that are traditionally landfilled at several of North Dakota’s lignite plants. This approach not only offers economic benefits for the lignite industry but also promotes sustainable development and use of North Dakota's fossil resources.

STANDARDS OF SUCCESS

The following standards will determine the success of this project:

1) **Identify and verify the characteristics of lignite ash materials that make them unsuitable for cement replacement**: The project should perform a rigorous analytical characterization of the selected materials to determine their chemical composition and morphology and compare against ASTM

standards relating to coal ashes for cement replacement. This will allow us to target specific material properties in the development of beneficiation process schemes.

2) **Demonstrate the technical feasibility of beneficiating lignite ashes to ASTM standards through a process route involving CO2M**: The project should demonstrate the feasibility of CO2M technology for beneficiation of ashes and dry sulfur scrubber residues produced at lignite-fired power plants. The testing should demonstrate achievement of relevant ASTM standards for fly ash for cement replacement and optimize the content of the beneficiated ashes for concrete application.
3) **Demonstrate positive economic and environmental impact**: The project should perform a high-level techno-economic assessment and carbon lifecycle analysis for selected materials and process schemes. The assessment should demonstrate the economic viability of the proposed pathways and quantify the environmental benefits, such as reduction in CO_2 emissions and waste elimination associated with the lignite industry.

BACKGROUND

Since 2008, UND CEM and Envergex LLC have partnered numerous times on successful projects of similar size and in related technical areas and have a strong history of development of innovative products in the energy and environmental field. This team was responsible for the development of the alkali solid sorbent-based CACHYS™ platform for CO_2 capture, of which the proposed accelerated direct CO2M screening tool is an extension, via multiple DOE-funded projects (DE-FE0007603 and DE-SC0010209) totaling over $4.7 million. Envergex and UND-CEM are partnering on the recently awarded SBIR project "Novel materials and Methods to Increase Soil Carbon", a Department of Agriculture funded project (USDA-NIFA-SBIR-008541), to upgrade biomass conversion residues using the team's accelerated direct CO2M technology to generate a product to be used for soil amendment. Additionally, both organizations were key technical subcontractors on a $5 million DOE- and NDIC-funded project to develop an alkali aerosol mitigation technology for high alkali coals (DE-FE00031756), with the technology used developed via a Phase I SBIR project that was awarded to Envergex LLC (DE-SC0015737). The findings of this alkali control technology will also be incorporated into the proposed project. Finally, the UND team also has world-class expertise, honed through a series of DOE- and NDIC-funded projects totaling more than $10 million, on rare earths and critical minerals, specifically relating to their recovery from unconventional resources.

Each of these ongoing and previous projects demonstrates the strong successful collaboration between UND and Envergex as well as the required technical background (CO_2 capture, gas-solid reaction systems, materials characterization, etc.). Our team has also secured the interest from several industry supporters who add significantly to the project's likelihood of success, both in providing samples for testing and information to direct our efforts.

QUALIFICATIONS

Dr. Johannes van der Watt is a Research Assistant Professor at UND CEM and will serve as Principal Investigator (PI) on the project. He brings over 5 years of energy research experience, particularly in chemical looping combustion sorbent manufacturing and testing (DE-FE0031534). He was an integral part of the development of the SBIR/STTR Phase II (DE-SC0011984) program to develop an evaluation methodology and classification system of oxygen carriers for Chemical Looping Combustion systems. Dr. van der Watt is an expert in gas-solid reaction systems, process modeling, and techno-economic assessments, which are key aspects of the proposed technical approach and scope of work.

Dr. Daba Gedafa is the Chair and Michael & Sitney Lodoen Endowed Professor of Civil Engineering at UND CEM. He has an extensive research experience with coal byproducts including bottom ash, slag, and fly ash for sustainable concrete and asphalt infrastructure. He has determined the optimum content of bottom ash and ground bottom ash with and without nano clay as a fine aggregate and cement replacement, respectively by comparing it to the compressive strength of cement-based concrete. Fresh properties, mechanical properties, and durability of optimum bottom ash and ground bottom ash-based concrete were determined. He also determined the maximum amount of cement that can be replaced by fly ash with and without nanomaterials while providing the equivalent or higher performance of concrete as compared to the control (cement-based concrete). He also determined the amount of fly ash that can be used to replace asphalt binder and mineral fillers for sustainable asphalt pavements. He is a registered professional engineer, Envision Sustainability Professional, and a fellow of the American Society of Civil Engineers.

Dr. Srivats Srinivasachar, He has 35 years of experience in power generation and manufacturing (coal combustion, cement, activated carbon, gypsum). At Envergex, and previously at ALSTOM Power, he developed and commercialized multiple technologies for power plant operations. At Envergex, he has developed products and services in three main areas: CO_2 capture; value-added product manufacturing; and control of mercury and alkali. Dr. Srinivasachar holds sixteen patents. Dr. Srinivasachar is also the inventor and lead developer of the CACHYS™ platform for CO_2 capture, including the accelerated direct CO2M technology based on the CACHYS™ platform and that is incorporated in this project.

Dr. Dan Laudal, Research Professor and Executive Director of the CEM Research Institute will assist Dr. Van der Watt in the management of the project. In addition to his management oversight role, Dr. Laudal will serve as a technical advisor to the project. He has 17 years of experience associated with management and execution of a wide range of energy-related R&D programs. Dr. Laudal was previously the lead research engineer on development of the CACHYS™ technology for CO_2 capture and has broad expertise in gas-solid reactions. Prior to his current role at UND CEM, he managed Minnkota Power Cooperative's development of Project Tundra[25] and served as Minnkota's environmental manager (2019-2021). As such, he has intimate familiarity with the operations of the Milton R. Young Station.

VALUE TO NORTH DAKOTA

The proposed project is part of a broader DOE-funded effort to evaluate an array of industrial wastes for CO2M and beneficial uses, but a major focus of the project will be on North Dakota's interests (lignite ashes), representing excellent leveraging of non-state funding. North Dakota lignite is unique in several key ways and power plants that use it as fuel have been designed to manage and take advantage of these unique properties. Some of the existing lignite plants, due to their fuel characteristics, boiler designs and air-pollution control device operations, are unable today to take advantage of the lucrative market for coal ash as partial cement replacement. This project targets these plants and proposes a new enabling pathway to beneficiate these ashes in a cost-effective approach, opening access to cement replacement markets. Importantly, this also has the benefit of eliminating or greatly reducing ash disposal costs and environmental liabilities.

Finally, in today's carbon constrained electric generation industry, several power plants are considering large capital investments in carbon capture technology. On its own, our proposed CO2M approach isn't expected to make a large impact on the plants' CO_2 emissions (but can provide a material revenue stream via carbon reduction benefits, e.g. 45Q). However, our approach integrates efficiently with alkali aerosol control strategies that could become a necessity to manage alkali ash fouling that is likely to be exacerbated by the high capacity factor operations plants will need to maintain after adding CO_2 capture.

MANAGEMENT

Dr. Van der Watt will serve as the project PI and the contact person for UND and will be responsible for the coordination of project activities. He will lead Tasks 1, 2, 3 and 5, and serve as technical advisor for Task 4. ***Dr. Laudal*** will support the PI in project management and will work with the project team to ensure all personnel, equipment, and other resources are available to conduct the project efficiently. He will also serve as a technical advisor across all project tasks. ***Dr. Gedafa*** will lead Task 4 focused on evaluating the properties and performance of the products for concrete applications. ***Dr. Srinivasachar*** will serve as the contact person for Envergex (see Appendix C). He will be involved in all tasks as a technical advisor. The Envergex team will also provide research engineers that will work on-site in the UND laboratories to support the experimental and analytical work proposed. The proposed project will also involve the training of multiple students, who will be mentored and advised by the senior personnel identified above. *The team's resumes are included in Appendix H.*

The organization chart is provided in Figure 5. The project management team is expected to include close coordination with the Lignite Energy Council's technical advisor to the NDIC and the DOE program manager. UND will also provide a resource manager who will be responsible for budget tracking and other administrative support functions.

Upon project initiation, the following items will be addressed throughout the project: 1) Monitor project scope, schedule, cost, and risk; 2) Update project plans periodically to reflect changes in scope, schedule, cost/risk; 3) Provide quarterly technical reports, participate in meetings, and present at conferences as required. We have prepared a preliminary risk chart, as presented in Table 2.

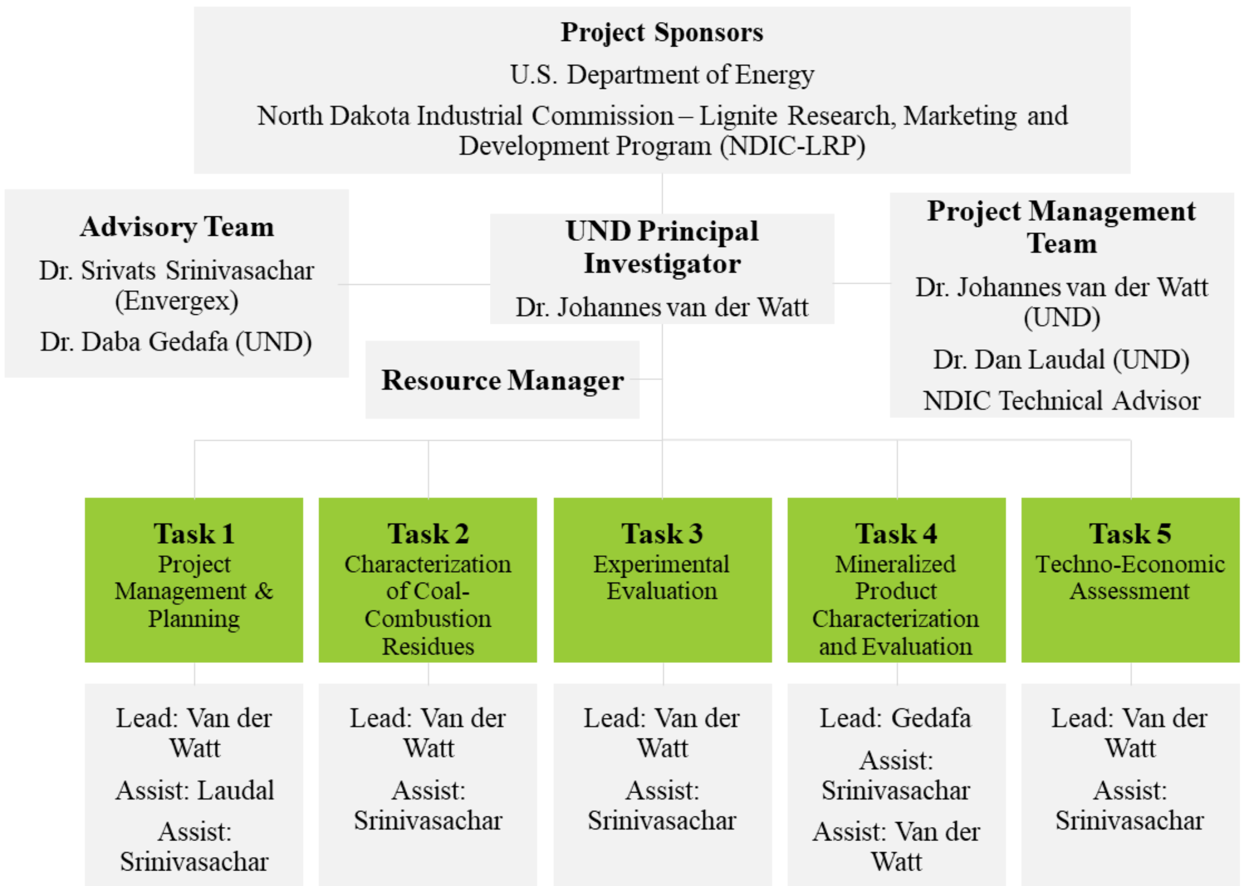


Figure 5: Organization chart.

Table 2: Perceived risks and mitigation strategies.

Perceived Risk	Risk Rating (Low, Med, High)			Mitigation/Response Strategy
	Probability	Impact	Overall	
Financial Risks:				
1 – A crucial activity unexpectedly requires substantial additional funds	Low	High	Low	Project and task managers will determine if any modification is possible to reduce cost and still meet project objectives. Additional funding will be sought if necessary.
Cost/Schedule Risks:				
1 – Task costs are overrun	Low	Med	Low	Budgets for each participant will be developed before work will begin. Costs will be monitored and if necessary, adjustments will be made to stay within the overall project budget.
2 – Task schedules are not met	Low	Med	Med	Schedules for each participant will be developed before work will begin. Regular internal review meetings will be held to stay on track. Additional personnel resources can be allocated to tasks that are behind schedule.
Technical/Scope Risks:				
1 – Unable to procure enough samples for assessment	Low	High	Low	We have secured letters of support from industry entities that have agreed to supply the necessary samples. We will also seek out additional samples from other entities throughout the project, as needed.
2 – Low performance potential determined from sample characterization and testing	Med	Low	Low	This study aims to perform a resource assessment. Poor performance is a valid result. We will adjust our focus to other types of materials or processes if one type is ruled out as being infeasible for this application.
3 – Equipment unavailable for analysis/testing	Low	High	Low	UND has access to all of the necessary equipment to complete the proposed scope. In the event of equipment malfunction, we will seek external options.
Management, Planning, and Oversight Risks:				
1 – Personnel availability	Low	High	Low	Utilize wide range of personnel expertise available at UND and project partners. UND has access to labor in the form of undergraduate/graduate students. Consider hiring of new personnel, as needed. All key personnel identified are committed and available to the project at their specified number of labor hours.
2 – Communication	Low	High	Low	Coordinate and schedule meetings and strictly follow communications plan.
3 – Cost tracking	Low	High	Low	A resource manager will be assigned to the project to assist the PI in tracking costs. Utilization of a project cost tracking system.
4 – Scheduling/meeting milestones	Low	High	Low	Planning system and communication implementation.

ES&H Risks:				
1 – Emissions	Low	Moderate	Low	Testing will be performed at small-scales and all emissions will be appropriately vented/treated according to UND's policies.
2 – Staff injuries resulting from system operation	Low	High	Low	Safety training according to UND and College of Engineering policies is required for all personnel who use laboratory equipment. An operational review meeting will be conducted prior to project testing.
External Factor Risks:				
1 – Unforeseen risks, e.g. natural disasters; social, legal, or technical changes; project economics; or changes in the political climate	Low	High	Low	Regular updates with project sponsors and project partners to solve issues as they arise.

TIMETABLE

This project has a duration of two years, tentatively starting on June 1, 2023, with the timetable, milestones and deliverables depicted in Table 3.

Table 3: Project timetable.

Task/Subtask/Milestone Description	Tentative Start Date	Tentative End Date
Task 1 - Project Management & Planning	06/01/23	05/31/25
Milestones/Deliverables		
Kickoff Meeting		**06/30/23**
Quarterly Report		**Quarterly**
Final Technical Report (90 days after project end date)		**08/29/25**
Task 2 - Characterization of Coal-Combustion Residues	06/01/23	11/28/23
Subtask 2.1 - Residue Procurement	06/01/23	08/30/23
Subtask 2.2 - Residue Characterization	08/30/23	11/28/23
Milestones/Deliverables		
Procure and prepare residues		**10/31/23**
Procure, prepare, characterize residue materials		**01/31/24**
Task 3 - Experimental Evaluation	11/29/23	05/27/24
Milestones/Deliverables		
Evaluate performance of residues in lab scale system		**07/31/24**
Task 4 - Mineralized Product Characterization and Evaluation	11/29/23	08/31/24
Subtask 4.1 - Reaction Product Characterization	11/29/23	03/31/24
Subtask 4.2 - Product Performance Testing	01/01/24	08/31/24
Milestones/Deliverables		
Description of residue and byproduct properties		**10/31/24**
Summary of product performance		**01/31/25**
Task 5 - Techno-Economic Assessment	09/01/24	05/29/25
Subtask 5.1 - Develop Alternative-Processing Schemes	09/01/24	11/30/24
Subtask 5.2 - Develop Process Flow Diagrams	11/30/24	03/30/25
Subtask 5.3 - Technical and Economic Analysis	11/30/24	03/30/25
Subtask 5.4 - Lifecycle Assessment (LCA)	02/01/25	05/29/25
Milestones/Deliverables		
Complete carbon lifecycle assessment		**01/31/25**
Developed alternative-processing schemes, process flow diagrams and technical-economic analysis		**04/30/25**

BUDGET

The amount of $250,000 (20% of total project cost) is requested from the NDIC. The breakdown of the budget into the DOE share and NDIC share of the funding along with the allocation of the funding is given in Table 4. Budget notes for UND are provided in Appendix D. Additional information about the Envergex commitment to the project and budget can be found in Appendix C.

Table 4: Cost breakdown.

Cost Category	DOE Share	NDIC Share	Total Project
Personnel	$222,242	$115,622	$337,864
Fringe Benefits	$35,439	$30,614	$66,053
Travel	$9,888	$519	$10,407
Materials/Supplies	$6,594	$3,400	$9,994
Equipment	$0	$0	$0
Envergex Subcontract	$449,878	$0	$449,878
Other Direct Costs	$123,944	$30,954	$154,898
Indirect Costs	$152,016	$68,890	$220,906
Total Project	**$1,000,000**	**$250,000**	**$1,250,000**

MATCHING FUNDS

The Department of Energy (DOE) Office of Fossil Energy and Carbon Management (FECM) will provide $1,000,000 in funding for project DE-FE0032244, with an 80/20 ratio match requirement. The DOE contract is currently being negotiated with UND. The award selection letter from DOE is included in Appendix E. For our DOE application, submitted several months ago, we were able to secure NDIC-LRP's provisional cost share commitment letter, which we include in Appendix F.

The DOE funding requires a 20% cost share, which we are requesting from NDIC in this proposal. In the event that the NDIC does not approve this funding request, the DOE project may be in jeopardy, as we will need to seek the required 20% cost share from other non-federal sources.

TAX LIABILITY

A copy of UND's Tax Liability Statement is provided in Appendix G

CONFIDENTIAL INFORMATION

Confidentiality request and confidential information is provided in Appendix A.

APPENDICES

Appendix A: Confidential Information

Appendix B: Letters of Support

Appendix C: Envergex Letter of Commitment and Budget Notes

Appendix D: Budget Notes for UND

Appendix E: DOE Award Selection Letter

Appendix F: NDIC – LRP Provisional Cost Share Commitment Letter

Appendix G: Tax Liability Statement

Appendix H: Resumes

REFERENCES

[1] Nguyen, Nicole, Benson, Steve, Nasah, Junior, and Srinivasachar, Srivats. Mitigation of Alkali Induced Aerosols. United States: N. p., 2022. Web. doi:10.2172/1907526.

[2] https://www.inforum.com/news/north-dakota/north-dakotas-biggest-power-plant-would-shut-down-for-3-years-if-permit-denial-sticks

[3] ASTM C 618-23, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, ASTM International, West Conshohocken, PA, 2023

[4] Ragipani, R., Escobar, E., Prentice, D., Bustillos, S., Simonetti, D., Sant, G. and Wang, B., 2021. Selective sulfur removal from semi-dry flue gas desulfurization coal fly ash for concrete and carbon dioxide capture applications. *Waste Management*, *121*, pp.117-126.

[5] https://pubs.usgs.gov/periodicals/mcs2023/mcs2023.pdf

[6] https://www.epri.com/research/products/3002002373

[7] S. A. Benson, S. Patwardhan, A. Ruud, A. Freidt and J. Joun, "Ash Formation and Partitioning in a Cyclone Fired Boiler," in *Impacts of Fuel Quality on Power Production*, Snowbird, Utah, 2014

[8] Thomas, M.D.A., 2007. *Optimizing the use of fly ash in concrete* (Vol. 5420). Skokie, IL, USA: Portland Cement Association.

[9] Pflughoeft-Hassett, Debra, Heebink, Loreal, Hassett, David, Dockter, Bruce, Eylands, Kurt, Buckley, Tera, and Zacher, Erick. JV Task 120 - Coal Ash Resources Research Consortium Research. United States: N. p., 2009. Web.

[10] Neto, J.D.S.A., De la Torre, A.G. and Kirchheim, A.P., 2021. Effects of sulfates on the hydration of Portland cement–A review. *Construction and Building Materials*, *279*, p.122428.

[11] Grutzeck, Michael W, DiCola, Maria, and Brenner, Paul. Building Materials made from Flue Gas Desulfurization By-products. United States: N. p., 2006. Web. doi:10.2172/881574.

[12] ASTM C1567-13, Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method), ASTM International, West Conshohocken, PA, 2013

[13] Zunino, F., Bentz, D.P. and Castro, J., 2018. Reducing setting time of blended cement paste containing high-SO3 fly ash (HSFA) using chemical/physical accelerators and by fly ash pre-washing. *Cement and Concrete Composites*, *90*, pp.14-26.

[14] Bittner, J. D., & Gasiorowski, S. A. (2005). Triboelectrostatic fly ash beneficiation: An update on separation technologies' international operations. *World of Coal Ash*, 11-15.

[15] Baker, L., Gupta, A. and Hrach, F., 2019. *World of Coal Ash (WOCA) Conference. University of Kentucky Center for Applied Energy Research, St. Louis, MO.*

[16] Chang, R. (2005) Beneficiation of fly ash containing mercury and carbon. *EPRI Technical Update, Palo Alto, CA*

[17] Veetil, S.P. & Hitch, M., 2020. Recent developments and challenges of aqueous mineral carbonation: a review. *International Journal of Environmental Science and Technology*, *17*(10), pp.4359-4380.

[18] Kelemen, P., *et al.*, 2019. An overview of the status and challenges of CO_2 storage in minerals and geological formations. *Frontiers in Climate*, *1*, p.9.

[19] Blondes, M.S., Merrill, M.D., Anderson, S.T. and DeVera, C.A., 2019. Carbon dioxide mineralization feasibility in the United States. *Scientific Investigations Report-US Geological Survey*, (2018-5079).

[20] https://www.blueplanetsystems.com/products

[21] https://patents.justia.com/patent/20210262320

[22] https://news.cornell.edu/stories/2022/12/cornell-startup-carbon-stone-enters-carbon-removal-pre-purchase-agreement-frontier

[23] https://www.sbir.gov/sbirsearch/detail/2271267

[24] https://engineering.und.edu/research/ies/labs-and-equipment.html

[25] https://www.netl.doe.gov/project-information?p=FE0031845

APPENDIX A: CONFIDENTIAL INFORMATION

Attached separately. Attachment includes justification for the confidentiality of specific information in this project proposal.

APPENDIX B: LETTERS OF SUPPORT

BASIN ELECTRIC POWER COOPERATIVE
A Touchstone Energy® Cooperative

March 20, 2023

Dan Laudal, Ph.D.
Research Professor and Director
Institute for Energy Studies
College of Engineering & Mines
University of North Dakota

Re: Letter of support for the University of North Dakota's proposal to the NDIC Lignite Research, Marketing and Development Program.

Dear Dr. Laudal,

Basin Electric Power Cooperative (BEPC) is pleased to provide this letter of support for your team's proposal to assess the resource potential of CO_2 mineralization materials that can be used to generate solid products for use in existing commercial markets. Carbon sequestration via mineralization has large potential as one of the mechanisms by which we can address increasing CO_2 concentrations in the atmosphere. We are particularly interested in this project because BEPC currently produces residues at our facilities that create a disposal expense for our company, but that could be used to create value-added products through CO_2 mineralization.

BEPC is a not-for-profit generation and transmission cooperative owned by 131-member cooperative systems across nine states serving 3 million customers. BEPC owns and operates two lignite-fired power plants in North Dakota that create residues that would be suitable for CO_2 mineralization. The Antelope Valley Station, near Beulah, ND, is a 900 MW 2-unit power plant that includes a dry SO_2 scrubber and fabric filter that produces dry scrubber ash. The Leland Olds Station is a 660 MW 2-unit power plant that produces lignite ash. Today, these ash materials are landfilled on-site at the plants at a cost to our company.

If the proposed project is awarded, we will support the project by engaging with your team in discussions about our residue materials and by providing representative samples for testing and analysis in your program. We look forward to working with your team.

Sincerely,

Gavin McCollam
Senior Vice President & Chief Operating Officer

JJS/SKW
Via electronic delivery (e-mail)

Minnkota Power Cooperative
A Touchstone Energy® Cooperative

5301 32nd Avenue South
Grand Forks, ND 58201

Phone 701.795.4000
www.minnkota.com

June 23, 2022

Dan Laudal, Ph.D.
Director | Institute for Energy Studies
College of Engineering & Mines
University of North Dakota

RE: Letter of Support for the University of North Dakota's proposal in response to the Department of Energy's Carbon Management Solicitation DE-FOA-0002614

Dear Dr. Laudal:

Minnkota Power Cooperative (MPC) is pleased to provide this letter of support for the University of North Dakota's proposal to assess CO_2 mineralization materials that can be used to generate solid carbonate products for use in existing commercial markets.

Carbon sequestration via mineralization has tremendous potential as one of the mechanisms by which we can address increasing CO_2 concentrations in the atmosphere. We are particularly interested in this project because MPC currently produces lignite coal ash that is landfilled at an expense for our company and can be used by the proposed technology to create value-added materials.

MPC is a generation & transmission electric cooperative that serves customers in eastern North Dakota and northwestern Minnesota. Our largest generation asset is the Milton R. Young Station (MRYS), a two-unit lignite coal-fired power plant near Center, North Dakota. In total, MRYS produces about 160,000 tons/year of lignite fly ash that is currently landfilled at a cost to MPC. We understand that our lignite ash has properties that could be valuable for CO_2 mineralization and that mineralization may open opportunities for converting our lignite ash into marketable products.

MPC is also in advanced stages of development of Project Tundra, a 4 million tons of CO_2/year capture and storage project, which is proposed for the MRYS. While Project Tundra will store its CO_2 by geologic storage, we are also interested in other opportunities for storage of the CO_2 produced at MRYS, such as through mineralization processes.

If the proposed project is awarded, we will support the project by engaging with your team in discussions about our ash materials and providing samples and available analyses as required to support your experimental testing and resource characterization. We look forward to hearing of a successful outcome.

Sincerely,

Craig J. Bleth, P.E.
Vice President of Power Supply
Minnkota Power Cooperative
Milton R. Young Station
3401 24th Street SW | Center, ND 58530

Office: (701) 794-7261
Cell: (701) 391-9815
Email: cbleth@minnkota.com
Web: minnkota.com

June 22, 2022

Dan Laudal, Ph.D.
Director | Institute for Energy Studies
College of Engineering & Mines
University of North Dakota
2844 Campus Rd. Stop 8153
Collaborative Energy Complex Room 246
Grand Forks, ND 58202-8153
daniel.laudal@und.edu
O: (701) 777-5745 | C: (701) 330-3241

RE: Letter of Support for the University of North Dakota's proposal in response to the Department of Energy's Carbon Management Solicitation DE-FOA-0002614

Dear Dr. Laudal:

Otter Tail Power Company (OTP) is pleased to provide this letter of support for the University of North Dakota's proposal to assess CO_2 mineralization materials that can be used to generate solid carbonate products for use in existing commercial markets. Carbon sequestration via mineralization has tremendous potential as one of the mechanisms by which we can address increasing CO_2 concentrations in the atmosphere. We are particularly interested in this project because OTP currently produces residues that are an expense for our company and can be used by the proposed technology to create value-added materials.

OTP is an investor-owned electric utility that provides electricity and energy services for residential, commercial, and industrial customers in Minnesota, North Dakota and South Dakota. Our service area spans approximately 70,000 square miles and is predominantly rural and agricultural.

OTP operates two coal-fired power plants that create alkaline-containing ash materials that could be utilized in the proposed technology. OTP is the operator and part owner of the Coyote Station near Beulah, ND. Coyote is an approximate 427 MW lignite-fired plant that has a dry scrubber fabric filter for SO_2 and particulate control. We typically dispose of more than 100,000 tons/year of dry scrubber ash product from Coyote in a landfill at a cost. OTP is also the operator and part owner of the Big Stone Plant near Big Stone City, SD. Big Stone is an approximate 475 MW subbituminous (PRB)-fired power plant. Big Stone also has a dry scrubber and fabric filter that typically results in more than 40,000 tons/year of ash product that needs to be disposed in a landfill. The dry scrubber ash from both plants has a composition that we understand may be suitable for your process.

If the proposed project is awarded, we will support the project by engaging with your team in discussions about our residue materials and potentially providing samples and analyses as required to support your experimental testing and design work. We look forward to hearing of a successful outcome.

Sincerely,

Mark Thoma

Mark Thoma
Manager, Environmental Services

APPENDIX C: ENVERGEX LETTER OF COMMITMENT AND BUDGET NOTES

Envergex LLC
10 Podunk Road
Sturbridge, MA 01566

July 22, 2022

Dr. Daniel Laudal
Director - Institute for Energy Studies
University of North Dakota (UND)
2844 Campus Rd Stop 8153
Grand Forks ND 58202-8153

Re: Support of the proposal entitled "**Resource Assessment of Industrial Wastes for CO_2 Mineralization**" submitted in response to DE-FOA-0002614

Dear Dr. Laudal,

This letter confirms Envergex LLC's commitment to supporting your proposed efforts in response to DE-FOA-0002614. We believe that UND's proposed project to evaluate the chemistry of various industrial wastes and determine their mineral carbonation performance presents a solid approach to developing a cost-effective CO_2 capture and sequestration method. This novel approach, developed through collaborative efforts between UND and Envergex LLC, and building on prior technology and projects on CO_2 capture, has the potential to provide industry clients with a unique industrial waste screening tool to assess the economic and environmental aspects of mineral carbonation.

Envergex will support the project to accomplish the following tasks outlined in the proposal.

Task 1 Project Management and Planning: The purpose of this task is coordination and planning of the project with the Office of Fossil Energy. Envergex will support UND in addressing all items related to monitoring and controlling project scope, cost, and schedule. Envergex will support UND in updating the project plan after initial negotiations and periodically as necessary. Envergex will provide input for quarterly technical and topical reports, participate in meetings and make presentations at contractor's conferences as required by DOE.

Task 2.0 – Characterization of Industrial Residues
This task will involve the characterization of multiple potential residue wastes from industries within the cement, ferrous- and non-ferrous metals, bio-based, and fossil fuel sectors. UND and Envergex will also evaluate additional resources outside of supporting sources, focusing on outreach to additional entities. Envergex will assist UND to conduct detailed characterizations to define all relevant properties of the materials that may affect the choice of pre- and post-mineralization processing. Envergex engineers will conduct tests along with UND personnel on the testing and analytical equipment.

Task 3.0 – Ex-situ direct mineralization testing: This task will focus on ex-situ mineralization, the carbonation of the industrial residues using CO_2-containing gas streams. The lab-scale testing will utilize the mineralization process that has been developed under the cooperative agreement USDA-NIFA-SBIR-008541, to evaluate the mineralization capacity of the residue materials. Envergex will lead the mineralization effort and support UND in the testing activities.

Task 4.0 – Mineralized Product Characterization and Evaluation:
The products from the CO_2 mineralization experiments will be characterized to assess the physical and chemical changes. The team will gather information on the samples' chemical compositions, mineralogy, and microstructures and compare the data to the virgin materials using various analytical techniques. The mineralized products that can potentially be used in concrete applications will be assessed for compatibility according to ASTM C618. Envergex will support UND in this task to conduct the characterization tests.

Task 5.0 – Mineralization Assessment Tool Development
This task is dedicated to combining the previous tasks' information into a holistic assessment tool that accounts for carbon lifecycle emissions associated with waste use for mineralization to identify viable usage pathways and their associated techno-economic feasibility. It includes five complimentary subtasks that amalgamate the findings and provides a clear description of how to use industrial wastes and what benefits can be expected. This assessment tool is intended to be expandable to other potential mineralization resources, including natural minerals and mining wastes. Envergex will support UND in performing energy and material balances, equipment sizing, equipment costing and operating cost definition. Envergex will support UND in preparing the Techno-Economic Evaluation report.

The overall budget for Envergex for the proposed work is $ 449,878 and includes labor and travel for work execution on the project. The estimated period of performance is 24 months, starting on or about April 10, 2023. A budget summary is attached.

Envergex LLC is committed to the development, testing, and commercialization of advanced energy and environmental control technologies. The development of a novel carbon mineralization assessment tool is a critical need for the US, and Envergex is pleased to be a participant in the subject proposal.

If you have any questions or comments, please feel free to contact me by phone at (508) 347-2933 or by e-mail at srivats.srinivasachar@envergex.com. I look forward to this opportunity to team with the University of North Dakota.

Sincerely,

Srivats Srinivasachar
President, Envergex LLC
E-mail: srivats.srinivasachar@envergex.com

Attachments: Budget Summary

BUDGET SUMMARY

Submitted by Envergex LLC as subcontractor to University of North Dakota

Applicant Name: University of North Dakota   Award Number: DE-FOA-0002614

Budget Information - Non Construction Programs

OMB Approval No. 0348-0044

Section A - Budget Summary

	Grant Program Function or Activity	Catalog of Federal Domestic Assistance Number	Estimated Unobligated Funds		New or Revised Budget		
			Federal	Non-Federal	Federal	Non-Federal	Total
	(a)	(b)	(c)	(d)	(e)	(f)	(g)
1.	Budget Period 1				$449,878.00	$0.00	$449,878.00
2.	Budget Period 2				$0.00	$0.00	$0.00
3.	Budget Period 3				$0.00	$0.00	$0.00
4.							
5.	Totals				$449,878.00	$0.00	$449,878.00

Section B - Budget Categories

6. Object Class Categories	Grant Program, Function or Activity				Total (5)
	Budget Period 1	Budget Period 2	Budget Period 3		
a. Personnel	$218,852.00	$0.00	$0.00		$218,852.00
b. Fringe Benefits	$118,749.00	$0.00	$0.00		$118,749.00
c. Travel	$9,280.00	$0.00	$0.00		$9,280.00
d. Equipment	$0.00	$0.00	$0.00		$0.00
e. Supplies	$0.00	$0.00	$0.00		$0.00
f. Contractual	$0.00	$0.00	$0.00		$0.00
g. Construction	$0.00	$0.00	$0.00		$0.00
h. Other	$0.00	$0.00	$0.00		$0.00
i. Total Direct Charges (sum of 6a-6h)	$346,881.00	$0.00	$0.00		$346,881.00
j. Indirect Charges	$102,997.00	$0.00	$0.00		$102,997.00
k. **Totals** (sum of 6i-6j)	$449,878.00	$0.00	$0.00		$449,878.00
7. Program Income					$0

SF-424A (Rev. 4-92)

Previous Edition Usable   Prescribed by OMB Circular A-102

APPENDIX D: BUDGET NOTES FOR UND

BUDGET SUMMARY AND BUDGET JUSTIFICATION

The following table gives the summary of the total project budget for University of North Dakota – College of Engineering and Mines)

BUDGET OUTLINE	F & A	41%
	Start date:	06/01/23
	End date:	05/31/25

DESCRIPTION	**Budget Period 1**	**Total Project**
SALARIES - REGULAR	39,043	39,043
SALARIES - OTHER (Graduate)	30,000	30,000
SALARIES - FACULTY	46,579	46,579
FRINGE BENEFITS	30,614	30,614
TOTAL PERSONNEL	146,236	146,236
TRAVEL	519	519
COMMUNICATIONS-PHONE		0
INSURANCE	0	0
RENTS/LEASES-EQUIPMENT & OTHER	0	0
RENTS/LEASES-BUILDING/LAND	0	0
OFFICE SUPPLIES (Publication costs)	0	0
REPAIRS	0	0
UTILITIES	0	0
SUPPLIES-IT SOFTWARE	0	0
SUPPLY/MATERIALS	3,400	3,400
SUPPLIES-MISCELLANEOUS		0
IT EQUIPMENT <$5,000	0	0
OTHER EQUIPMENT <$5,000	0	0
FEES-OPERATING FEES & SERVICES	17,870	17,870
FEES-PROFESSIONAL FEES & SERVICES		0
PROFESSIONAL DEVELOPMENT	0	0
FOOD AND CLOTHING	0	0
WAIVERS/SCHOLARSHPS/FELLOWSHPS	13,084	13,084
TOTAL OPERATING	34,873	34,873
EQUIPMENT >$5,000	0	0
TOTAL EQUIPMENT	0	0
TOTAL DIRECT COST	181,110	181,110
TOTAL INDIRECT COST	68,890	68,890
TOTAL COST	250,000	250,000

Personnel and Fringe Benefits

Salary estimates are based on the scope of work, and the labor rate used for specific personnel is based on their current salary rate. The table below gives the personnel cost breakdown. Any reference to hours worked on this grant is for budgeting purposes only.

Fringe benefits are estimated for proposal purposes only. On award implementation, only the true cost of each individual's fringe benefit plan will be charged to the project. Fringe benefits are estimated based upon the current rates for each labor category.

Personnel	Personnel Costs	Fringe Rate	Fringe Benefits
SALARIES - REGULAR			
Engineer	$ 33,400	40.91%	$ 13,664.40
Undergraduate student worker	$ 3,218	0.50%	$ 16.09
Resource Manager	$ 2,424	40.00%	$ 969.75
SALARIES - OTHER (Graduate)			
Graduate Research Assistant	$ 30,000	0.50%	$ 150.00
SALARIES - FACULTY			
Johannes van der Watt	$ 28,875	40%	$ 11,594.27
Dan Laudal	$ 3,828	27%	$ 1,028.53
Daba Gedafa	$ 13,876	23%	$ 3,190.79
Total	**$ 115,622.30**		**$ 30,613.83**

Travel

Purpose of Travel	# of Days	# of People	Flight	Per diem	Hotel	Light Pickup	Total	Basis of estimate
Site Visit: Minnkota Power Cooperative, Ottertail Power Company	1	1	$ -	$ 59	$ -	$ 460	$ 519	Current GSA rates
Total							**$ 519**	

Equipment

None.

Supplies

The supplies budget is an estimate based upon experience in conducting sample analyses.

Supplies	Quantity	Unit Cost	Total	Justification
CO2 gas bottle	2	$33	$66	Past invoice
Gas bottle rental, months	9	$15	$135	Past invoice
O2 bottle	2	$33	$66	Past invoice
N2 bottle	2	$33	$66	Past invoice
Grinding media	4	$96	$384	Past experience
Mill gaskets	8	$60	$480	Past experience
Mill maintenance	1	$1,500	$1,500	Past experience
Sample Containers	1	$200	$200	Online Quote
Cement	4	$20	$80	Online Quote
Sand	4	$96	$384	Online Quote
Aggregate	4	$10	$40	Online Quote
Total			**$3,400**	

Other

Analytical costs and Professional Service Fees.

Analytical	Quantity	Cost	Total	Justification
Inductively-Coupled Plasma Analysis	20	$49	$980	Chemical composition of samples
X-Ray Diffraction	40	$32	$1,280	Crystalline phases in ash samples
Scanning Electron Microscopy	20	$49	$980	Morphology of solid samples
Sample preparation	100	$15	$1,500	Sample preparation for tests
Sulfur Analysis	10	$25	$250	Chemical composition of samples
TGA-DSC Analysis	40	$65	$2,600	Degree of mineralization
TC/TIC	40	$32	$1,280	Form of carbon in materials
TCLP	10	$750	$7,500	Leachability of products
Total			**$16,370**	

Professional Fees & Services	Quantity	Cost	Total	Justification
Waste disposal	1	$1,500	$1,500	Past experience
Total	**$1,500**			

Subcontractor Costs

None

Indirect Costs

Indirect Costs	
F&A Rate	41%
Fees-Professional Fees & Services	$ 7,327
Total Personnel	$ 59,957
Travel	$ 213
Supply/Materials	$ 1,394
Total	**$ 68,890**

Budget summary

Cost Category	**DOE Share**	**NDIC Share**	**Total Project**
Personnel	$222,242	$115,622	$337,864
Fringe Benefits	$35,439	$30,614	$66,053
Travel	$9,888	$519	$10,407
Materials/Supplies	$6,594	$3,400	$9,994
Equipment	$0	$0	$0
Envergex Subcontract	$449,878	$0	$449,878
Other Direct Costs	$123,944	$30,954	$154,898
Indirect Costs	$152,016	$68,890	$220,906
Total Project	**$1,000,000**	**$250,000**	**$1,250,000**

APPENDIX E: DOE AWARD SELECTION LETTER

January 25, 2023

SENT VIA ELECTRONIC MAIL

University of North Dakota
Attn: Johannes van der Watt
johannes.vanderwatt@und.edu

SUBJECT: Selection of Application for Negotiation Under Funding Opportunity Announcement Number DE-FOA-0002614, Carbon Management (Round 1)

Dear Johannes van der Watt:

We are pleased to provide this update on your application. The Office of Fossil Energy and Carbon Management within the Department of Energy (DOE) has completed its evaluation of your application submitted in response to the subject Funding Opportunity Announcement (FOA). The application below has been recommended by the Office of Fossil Energy and Carbon Management for negotiation of a financial award (Note: This notification does not guarantee Federal Government funding, as funding will only be obligated upon completion of successful negotiations):

Application: Resource Assessment of Industrial Wastes for CO_2 Mineralization
Principal Investigator: Johannes van der Watt
Application Control Number: GRANT13684666

DOE intends to make a public announcement of the selections and requests that your organization and subrecipients do not make any announcement of your selection prior to the DOE announcement. At the time of the announcement, we will provide you with a link to the announcement and inform you that the embargo has officially been lifted via subsequent email. You will then be free (and encouraged) to announce your award publicly.

Receipt of this letter does not authorize you to commence with performance of the project. DOE makes no commitment to issue an award and assumes no financial obligation with the issuance of this letter. Applicants do not receive an award until award negotiations are complete and the Contracting Officer executes the funding agreement. Only an award document signed by the Contracting Officer obligates DOE to support a project.

The award negotiation process may take up to 90 days. You must be responsive during award negotiations (i.e., provide requested documentation) and meet the stated negotiation deadlines. Failure to submit the requested information and forms by the stated due date, or any failure to conduct award negotiations in a timely and responsive manner, may cause DOE to cancel award negotiations and rescind this selection. DOE reserves the right to terminate award negotiations at any time for any reason.

Please complete the following items and submit to DOE no later than Feb. 3, 2023:

- Pre-Award Information Sheet (available at https://www.netl.doe.gov/business/business-forms/financial-assistance)

If your organization or any subrecipient anticipates utilizing foreign nationals (FNs) in the performance of the award, your organization must:

- Complete the "Foreign National Participation Document" for all FNs planned to participate on the award. Submit the completed document to basicinfo@netl.doe.gov with a courtesy copy to the assigned Project Manager (PM) and DOE Award Administrator.

  Upon receipt of the completed "Foreign National Participation Document," DOE will create secured file sharing drop box folder(s) for submission of additional information for **FNs in Principal Investigator (PI)/Co-PI roles and for FNs from countries identified on the U.S. Department of State's list of State Sponsors of Terrorism** (https://www.state.gov/state-sponsors-of-terrorism/). Additional information is **NOT** required for any other FNs planned to participate on the award.

- Complete the "Foreign National Participation **Data** Document" for PIs/Co-PIs and for FNs from countries identified as State Sponsors of Terrorism. The Foreign National Participation **Data** Document and all required attachments for **FNs in Principal Investigator (PI)/Co-PI roles and for FNs from countries identified on the U.S. Department of State's list of State Sponsors of Terrorism** must be uploaded to the secure file sharing drop box folder(s) provided by DOE. The assigned PM will contact your organization's FN point-of-contact in the event there are issues with the submission.

NOTE: The "Foreign National Participation Document" and Foreign National Participation **Data** Document are located at https://www.netl.doe.gov/business/business-forms/financial-assistance under Post Selection Forms/Information.

Once these steps are completed, all FNs identified on the "Foreign National Participation Document", **except for** **FNs from countries identified on the U.S. Department of State's list of State Sponsors of Terrorism** are authorized to commence work as of the award effective date unless determined otherwise by DOE. **FNs from countries identified on the U.S. Department of State's list of State Sponsors of Terrorism are not permitted to participate on the award until written authorization is received from the Contracting Officer.** The DOE reserves the right to request additional information or deny participation of any FN at any time.

Please provide the requested documents to the attention of Kate Hubbs, who is the DOE Award Administrator from the Finance and Acquisition Center handling the administrative portion of your application. Kate Hubbs can be reached at anna.hubbs@netl.doe.gov. Johnathan Moore is the DOE Project Manager from the Technology Development Center handling the technical portion of your application and can be reached at johnathan.moore@netl.doe.gov.

Sincerely,

Angela Bosley
Contracting Officer
Finance and Acquisition Center

cc: FOA File
Basicinfo@netl.doe.gov
Johannes van der Watt, Principal Investigator, johannes.vanderwatt@und.edu
Johnathan Moore, Project Manager, johnathan.moore@netl.doe.gov
Kate Hubbs, DOE Award Administrator, anna.hubbs@netl.doe.gov

APPENDIX F: NDIC – LRP PROVISIONAL COST SHARE COMMITMENT LETTER

June 21, 2022

Dr. Dan Laudal
Director | Institute for Energy Studies
College of Engineering & Mines
University of North Dakota
2844 Campus Rd. Stop 8153
Collaborative Energy Complex Room 246
Grand Forks, ND 58202-8153
daniel.laudal@und.edu
O: (701) 777-5745 | C: (701) 330-3241

Re: Support for the University of North Dakota's proposal to Area of Interest 4 – Carbon Storage Technology under Department of Energy funding opportunity DE-FOA-0002614

Dear Dr. Laudal,

The Lignite Energy Council and closely aligned Lignite Research Council are working together to support technologies to enhance the utilization of lignite coal. As such, we are pleased to support the University of North Dakota's proposal to develop a database and help identify how coal ash and associated materials can be used as a carbon management material. Your proposal has strong synergies with lignite coal users in North Dakota and can help provide the opportunity to preserve and enhance the development of the state's abundant lignite resources.

As a part of this project, the North Dakota Industrial Commission (NDIC) through the Lignite Research, Development and Marketing Program will provide $250,000 in cash cost-share subject to a project award by the U.S. Department of Energy (DOE). It is understood that this lignite research program funding will provide cost-share to federal funding from the DOE; therefore, the Lignite Research Council certifies that its cost-share funding will comprise nonfederal dollars and will not be used as a federal match on any other project. The cash support will be contingent upon submitting a proposal to the Lignite Research, Development and Marketing Program and subsequent approval by the Lignite Research Council and the North Dakota Industrial Commission.

Sincerely,

Mike Holmes
Executive Vice President of Research & Development
Lignite Energy Council

APPENDIX G: TAX LIABILITY STATEMENT

Industrial Commission

Tax Liability Statement

Applicant:
University of North Dakota

Application Title:
Assessment of Lignite-Based Industrial Residues for Value-Added Product Creation through CO2 Mineralization

Program:

- ☑ Lignite Research, Development and Marketing Program
- ☐ Renewable Energy Program
- ☐ Oil & Gas Research Program
- ☐ Clean Sustainable Energy Authority

Certification:
I hereby certify that the applicant listed above does not have any outstanding tax liability owed to the State of North Dakota or any of its political subdivisions.

Karen Katrinak
____
Signature

Karen Katrinak
Proposal Development Officer
____
Title

March 31, 2023
____
Date

APPENDIX H: RESUMES

Dr. Johannes George van der Watt, Research Engineer, Institute for Energy Studies University of North Dakota (UND)

Education and Training

University of North Dakota	Chemical Engineering	Ph.D. 2019
North-West University, South Africa	Chemical Engineering	M. Eng. 2013
North-West University, South Africa	Chemical Engineering	B. Eng. 2011

Research and Professional Experience

2022-Present Research Assistant Professor, UND Institute for Energy Studies

2019-2022 Research Engineer, UND Institute for Energy Studies

2015-2019 Graduate Research Assistant, UND Institute for Energy Studies

2013-2014 Junior Process Engineer, Pro-Op Industries (South Africa)

2012-2013 Graduate Research Assistant, North-West University (South Africa)

Publications

- Nasah, Junior, **Van der Watt, Johannes George**, Mann, Michael, Musich, Mark, Srinivasachar, Srivats, Nelson, Teagan, Koenig, Aaron, Fuka, Matt, Benson, Alex, and Benson, Steve. Low Cost Recyclable Oxygen Carrier and Novel Process for Chemical Looping Combustion. United States: N. p., 2022. Web. doi:10.2172/1846668.
- Nelson, T., **Van der Watt, J.G.**, Laudal, D., Feilen, H., Mann, M. and Srinivasachar, S., 2019. Reactive jet and cyclonic attrition analysis of ilmenite in chemical looping combustion systems. *International Journal of Greenhouse Gas Control*, 91, p.102837.
- **Van der Watt, Johannes George**, "Modeling And Improving Oxygen Carrier Performance In Chemical Looping Combustion Systems" (2019). *Theses and Dissertations*. 2871. https://commons.und.edu/theses/2871

- **Van der Watt, J.G.**, Laudal, D., Krishnamoorthy, G., Feilen, H., Mann, M., Shallbetter, R., Nelson, T. and Srinivasachar, S., 2018. Development of a Spouted Bed Reactor for Chemical Looping Combustion. *Journal of Energy Resources Technology*, 140(11).
- Srinivasachar, S., Nelson, T., **Van der Watt, J.**, Feilen, H., Laudal, D., & Mann, M. (2018). *Methodology for Attrition Evaluation of Oxygen Carriers in Chemical Looping Systems: Final Scientific/Technical Report-Phase II* (No. DOE-Envergex-PhII-SC0011984). Envergex LLC.

Synergistic Activities

- Dr. Van der Watt has performed multiple combustion-based testing for technology development and/or verification, including oxygen carrier development for combustion and CO_2 capture, activated carbon manufacturing, and various sorbents and catalyst testing for fuel conversion.
- Principal areas of expertise relate to advanced combustion systems, computational fluid dynamics (CFD), and process simulation.
- He has led the efforts to model UND-IES' novel chemical looping combustion technology on MFiX CFD software and designed UND's laboratory-scale gasifier equipment. As part of these projects, he also developed the heat and mass balance for a 580 MW CLC facility and 10 MWe gasifier using ASPENPlus®, respectively.
- Experience in process development, laboratory- and pilot-scale testing, and experimental design
- Current work focused on producing hydrogen and valuable carbon from fossil and renewable resources, carbon dioxide capture, and waste coal remediation with ancillary power production.

Daba S. Gedafa, Chair and Michael & Sitney Lodoen Endowed Professor of Civil Engineering, Civil Engineering Department, University of North Dakota

Dducation and Training

2008-2009 Postdoctoral, Civil Engineering Department, Kansas State University, Manhattan, KS.

2009 Ph.D. Civil Engineering, Kansas State University, Manhattan, KS.

2005 M.S. Civil Engineering, IIT Bombay, Mumbai, India.

2001 B.S. Civil Engineering, Addis Ababa University, Addis Ababa, Ethiopia.

Research and Professional Experience

2022-present Professor Department of Civil Engineering, UND.

2017-2022 Associate Professor Department of Civil Engineering, UND.

2011-2017 Assistant Professor Department of Civil Engineering, UND.

2009-2011 Assistant Professor in Residence Department of Civil Engineering, University of Connecticut, Storrs, CT.

2008-2009 Postdoctoral Research Associate, Department of Civil Engineering, Kansas State University, Manhattan, KS.

2005-2008 Graduate Research Assistant, Department of Civil Engineering, Kansas State University, Manhattan, KS.

Publications (Selected from over 60)

- Melaku, R., Ness, S., **Gedafa, D.S.,** and Suleiman, N. (2022). "Investigating the Use of Fly Ash for Sustainable Asphalt Binders," *Proceedings of the 11th International Conference on the Bearing Capacity of Roads, Railways, and Airfields, June 28-30, 2022*, Trondheim, Norway, Volume 3, pp. 436-444.
- Tolliver, S. and **Gedafa, D.S.** (2016). "Investigating the Use of Fly Ash and Nanomaterials for Sustainable Concrete Infrastructure," *International Journal of Engineering Research & Technology*,

Vol. 5, No. 7, pp. 173-177.

- **Gedafa, D.S.**, Hossain, M., Romanoschi, S., and Gisi, A.. (2010). "Comparison of Moduli of Kansas Superpave Asphalt Mixes," *Transportation Research Record: Journal of the Transportation Research Board,* Vol. 2154, pp 114-123.
- Abolghasem Yazdani* and Daba S. Gedafa. "Effect of Nanopolymer Modified Binder on Hot Mix Asphalt," *Proceedings of the International Conference on Transportation & Development*, May 31-June 3, 2022, Seattle, WA, pp. 190-200.
- Jun Liu*, Robeam S. Melaku*, Daba S. Gedafa, and Nabil Suleiman. (2021). "Performance Comparison of HMA Mixes Used on Different Levels of North Dakota's Highway Performance Classification System," *ASCE International Airfield and Highway Pavements Conference 2021,* pp. 137-145.

Synergistic Activities

- Principal Investigator: He has an extensive research experience with coal byproducts including bottom ash, slag, and fly ash for sustainable asphalt and concrete infrastructure. He received three grants from the NDIC. He determined the amount of fly ash that can be used to replace asphalt binder and mineral fillers for sustainable asphalt pavements. He has also determined the optimum content of bottom ash and ground bottom ash with and without nano clay as a fine aggregate and cement replacement, respectively by comparing it to the compressive strength of cement-based concrete. Fresh properties, mechanical properties, and durability of optimum bottom ash and ground bottom ash-based concrete were determined. He also determined the maximum amount of cement that can be replaced by fly ash with and without nanomaterials while providing the equivalent or higher performance of concrete as compared to the control (cement-based concrete).
- Professional Certifications: He is a registered professional engineer, Envision Sustainability Professional, and a fellow of the American Society of Civil Engineers.
- Presentations: He has made more than 20 presentations at national and international conferences.

Dr. Daniel A. Laudal, Executive Director, UND College of Engineering & Mines Research Institute

Education and Training

University of North Dakota	Chemical Engineering	Ph.D. 2017
University of North Dakota	Chemical Engineering	B.S. 2006

Research and Professional Experience

2023-Present Executive Director, UND College of Engineering & Mines Research Institute

2023-Present Research Professor, UND Dept. of Chemical Engineering

2021-Present Director, UND Institute for Energy Studies

2019-2021 Environmental Manager / Project Tundra Project Manager, Minnkota Power Cooperative

2016-2018 Manager: Major Projects, UND Institute for Energy Studies

2012-2015 Research Engineer, UND Institute for Energy Studies

2008-2012 Research Engineer, UND Energy & Environmental Research Center

2006-2008 Field Engineer, Schlumberger Oilfield Services

Select Publications

- **Laudal, D.**, Benson, S., Addleman, S., Palo, D. "Leaching behavior of rare earth elements in Fort Union lignite coals of North America." International Journal of Coal Geology 191 (2018) 112-124.
- **Laudal, D.**, Benson, S., Addleman, S., Palo, D. "Rare earth elements in North Dakota lignite coal and lignite-related materials." ASME Journal of Energy Resources and Technology 140 (2018).
- Park, D., Middleton, A., Smith, R., Deblonde, G., **Laudal, D.,** Theaker, N., Hsu-Kim, H., Jia, Y. "A biosorption-based approach for selective extraction of rare earth elements from coal byproducts." Separation and Purification Technology. Volume 241:116726. June 2020.
- Van der Watt, J.G., **Laudal, D**., et al "Development of a spouted bed reactor for chemical looping combustion." Journal of Energy Resources and Technology. 140(11), 112002 (8 pages), Nov 2018.
- Benson, S., Srinivasachar, S, **Laudal, D**., Browers, B. "Evaluation of Carbon Dioxide Capture from

Existing Coal Fired Plants by Hybrid Sorption using Solid Sorbents." Final Technical Report. US Department of Energy Award Number: DE-FE0007603. May 2015

- Mann, M; **Laudal, D.**; Benson, S. "Maintaining Coal's Prominence in a Carbon Constrained World." Conference Proceedings: 2017 International Conference on Coal Science and Technology and 2017 Australia-China Symposium on Energy. September 25-29, 2017. Beijing, China.

Patents

- **Laudal, D.,** Benson, S. "Rare earth element extraction from coal." U.S. Patent No. 10,669,610. 2017
- Theaker, N., **Laudal, D.,** Lucky, C. "Generation of rare earth elements from organically associated leach solutions." U.S. Patent Application No. 17/519,346. Filed May 2022.
- Theaker, N., **Laudal, D.** "Method for leaching rare earth elements and critical minerals from organically associated materials." U.S. Patent Application No. 17/519,341. Filed May 2022.

Synergistic Activities

Dr. Laudal's primary areas of technical expertise include critical minerals recovery processes, advanced fuel conversion processes and carbon capture, utilization and storage. Of specific relevance to the proposed project is Dr. Laudal's experience with the development of the UND/Envergex CACHYS™ technology and in performing TEAs for many technologies. While at Minnkota, he was also previously the project manager for a $1.5B world-scale carbon capture and storage project, currently under development in North Dakota (Project Tundra). Dr. Laudal brings a unique mix of early-stage technology development, project management and commercial project development expertise. His role in the proposed project will be as a technical advisor and to support the PI in project management.

Dr. Srivats Srinivasachar, President, Envergex LLC

Education and Training

Boston University, School of Management	Master of Business Administration	M.B.A. 2004
Massachusetts Institute of Technology	Chemical Engineering	Sc.D. 1986
Indian Institute of Technology, India	Chemical Engineering	B. Tech. 1981

Research and Professional Experience

2006-Present President, Envergex LLC, Sturbridge, MA

1999 – 2006 ALSTOM Power, Inc. (1993 – 1999: ABB Combustion Engineering, Inc. Windsor, CT)

1986-1993 Physical Sciences Inc. Andover, MA

Select Publications

- **Srinivasachar, S.**, 2012. *Sequestration Capture of* CO_2 *by Hybrid Sorption (CACHYS-TM) for Existing Coal-Fired Plants: STTR-Phase I Report* (No. DOE/SC/0004476-1). Envergex LLC, Sturbridge, MA (United States).
- **Srinivasachar, S.**, Nelson, T., Nasah, J., Laudal, D. and Benson, S.A., 2017. *Mitigation of Aerosol Emissions from Solvent-based Post-Combustion* CO_2 *Capture Systems: Final Scientific/Technical Report-Phase I STTR* (No. DOE-ENVERGEX-SC0015737). Envergex LLC, Sturbridge, MA (United States).
- Senior, C.L., Bool III, L.E., **Srinivasachar, S.**, Pease, B.R. and Porle, K., 2000. Pilot scale study of trace element vaporization and condensation during combustion of a pulverized sub-bituminous coal. *Fuel Processing Technology*, *63*(2-3), pp.149-165.
- Benson, S.A., Crocker, C.R., Hanson, S.K., McIntyre, K.A., Just, B.J., Raymond, L.J., Pflughoeft-Hassett, D.F, **Srinivasachar, S.**, Barry, L.T. and Doeling, C.M., "JV Task 115-Activated Carbon Production from North Dakota Lignite – Phase IIA," Final Report, U.S. Department of Energy Cooperative Agreement No. DE-FC26-98FT40321, June 2008

- Van der Watt, J.G., Laudal, D., Krishnamoorthy, G., Feilen, H., Mann, M., Shallbetter, R., Nelson, T. and **Srinivasachar, S.**, 2018. Development of a Spouted Bed Reactor for Chemical Looping Combustion. *Journal of Energy Resources Technology*, 140(11).

Select Patents

U.S. Patent 8,840,706, "Capture of carbon dioxide by hybrid sorption"

U.S. Patent 6,749,681, "Method of Producing Cement Clinker and Electricity"

U.S. Patent 7,981,835, "System and method for coproduction of activated carbon and steam/electricity"

U.S. Patent 8,277,542, "Method of capturing mercury from flue gas"

U.S. Patent 8,069,797, "Control of Mercury Emissions from Solid Fuel Combustion"

Synergistic Activities

Expertise in energy and environmental engineering, power plant systems, and cross-industry product development; Led product/process development groups - ALSTOM Power Inc. (now a GE company); Secured multiple patents and published over 50 technical papers. Dr. Srinivasachar is developing carbon capture technologies for fossil-fired power plants on an ARPA-E project (DE-AR0001314); has developed models for integrating energy storage with fossil power plants (DE-SC0020863); is demonstrating on a commercial scale sorbent injection for aerosol mitigation in power plants DE-FE0031756 - project originated from STTR funding; team member Coal FIRST FEED study (Coal and Gas Boiler and Turbine Concept) DE-FE0031995. Dr. Srinivasachar is also the inventor of multiple activated carbon technologies which he scaled from pilot-scale to successful demonstration at three full-scale plants. About 250,000 lb of product have been supplied to six power plants for emission control.