

# Olivine-Based Cement Supplement Utilizing $CO_2$ by Direct Air Capture May Reduce $CO_2$ Emissions from Cement Production

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**Background/Objective:** Manufacturing of the most commonly used construction material, Portland Cement, is associated with significant  $CO_2$  emission. We aim to study the environmental effect of Magnesium Silicate mineralization for cement substitution utilizing Carbon Dioxide ( $CO_2$ ) captured from Direct Air Capture (DAC) systems. We hypothesize that the carbon emissions during conventional production of cement could be reduced by 20%-30% during the proposed process as 40% of Portland cement is replaced with the supplementary cementitious material (SCM) considering all variables including carbon emissions during the DAC, mineralization, and transportation.

**Methods:** A life cycle assessment (LCA) was performed to evaluate the environmental impacts of integrating Magnesium Silicate as a cement substitute. The study utilized cradle-to-gate system boundaries focusing on  $CO_2$  emissions, analyzing the carbon emissions of the cement and SCM making process.

**Results:** Substituting cement with mineralized Magnesium Silicate using  $CO_2$  from Direct Air Capture could reduce  $CO_2$  emissions by over 16% compared to traditional Portland cement depending on the amount of Cement replaced with the SCM alongside transportation needs.

**Conclusion:** The findings of our study demonstrate that Magnesium Silicate mineralization is a viable solution for reducing the environmental impact of cement production.

**Keywords:** Direct Air Capture(DAC), Cement manufacturing,  $CO_2$  Emission, Supplementary Cementitious Material (SCM)

## Introduction

Under the Paris Agreement, 197 countries agreed to limit global warming by requiring a net zero  $CO_2$  emissions by 2050. Furthermore, Fankhauser et al., 2021 report that even if anthropogenic  $CO_2$  emissions are completely removed, warming trends would continue to be seen for possibly centuries. To attain net zero carbon emissions by 2050, two things must be achieved: reducing  $CO_2$  emissions almost entirely, and capture as well as storage of previous emissions. Significant progress has been made in reducing carbon emission by advancement in renewable energy, battery-powered transportation systems, and use of solar energy<sup>1</sup>.

Technological evolution in Carbon Capture, Utilization, and Storage (CCUS) remains crucial for mitigating the need to decarbonize heavy industries like steel and cement production, a goal unlikely achievable just by using renewable energy and efficiency improvements. CCUS technologies capture  $CO_2$  emissions at their source, preventing them from entering the atmosphere, then storing  $CO_2$  underground in geological formations or utilizing  $CO_2$  in various products, such as building materials or fuels. Current methods for CCUS include DAC, and mineralization. DAC works in two different ways, liquid solvent, or solid sorbent. Solid sorbent technology currently

seems very feasible and is more industrialized<sup>2</sup>.

$CO_2$  mineralization is a process that not only securely stores carbon dioxide but also converts it into valuable products, such as building materials. This approach involves reacting  $CO_2$  with minerals to form stable carbonate compounds, effectively turning greenhouse gas into solid materials like calcium carbonate or magnesium carbonate<sup>3</sup>. These carbonates can be used in various industries, particularly in the production of concrete and construction materials, thus creating an economic incentive to capture and utilize  $CO_2$ .

The process of  $CO_2$  mineralization can occur through several methods, including in situ, ex situ, direct, or indirect approaches. In situ mineralization involves injecting  $CO_2$  directly into underground rock formations, such as basalt or peridotite, where it reacts with naturally occurring minerals to form stable carbonates<sup>4</sup>. This method provides long-term and secure  $CO_2$  storage while enhancing the stability of geological formations, reducing the risk of leakage. In contrast, ex situ mineralization takes place in a controlled industrial setting where  $CO_2$  reacts with minerals or industrial wastes, like slag or fly ash<sup>4</sup>. This method not only securely stores  $CO_2$  but also produces valuable by-products, such as construction aggregates or SCM, which can reduce the need for mined raw materials.

Supplementary Cementitious Materials (SCMs) are made

with carbon dioxide and can further reduce the carbon emissions during cement production. Common SCMs include fly ash, and slag cement (ground granulated blast-furnace slag). These materials are often industrial byproducts, making their use a sustainable alternative that reduces the carbon footprint of concrete production. SCMs improve the durability, workability, and strength of concrete while reducing its carbon footprint. The chemical reactions involved in  $CO_2$  mineralization vary depending on the process and the types of minerals used. For in situ and ex situ processes, common reactions include the formation of carbonates from calcium and Magnesium Silicates which then can be used as SCMs:

For calcium-containing minerals, the reaction is<sup>5</sup>:  $CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$  For magnesium-containing minerals, the reaction is<sup>5</sup>:  $Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2$

Cement is produced on a massive scale, with 4.1 billion tons being produced in 2023<sup>6</sup>. Cement production releases an average of 0.83 Ton  $CO_2$ /Ton Cement, suggesting about 3.403 billion tons of  $CO_2$  released in 2023. Thus, cement production accounts for 9.1% of 37.4 billion tons of  $CO_2$  released in 2023 per International Energy Agency (IEA)<sup>7</sup>. Although progress has been made in renewable energy, DAC, and mineralization; minimal carbon mitigation strategies are adopted in cement production. A few companies have led these efforts. CarbonCure injects captured  $CO_2$  into concrete during mixing, to permanently sequester  $CO_2$  and improve the compressive strength of the concrete<sup>8</sup>. Another company Carbon8, also offers a unique approach by combining  $CO_2$  capture with mineralization, using industrial waste materials like fly ash and steel slag to create carbonated aggregates for construction. This process not only captures  $CO_2$  but also transforms waste into valuable construction products, supporting a circular economy and reducing landfill use.

By combining DAC with mineralization,  $CO_2$  is converted into stable carbonates, which can then be utilized as a replacement for cement. For such a process when Olivine was used as a feedstock for mineralization in producing cement replacements it had the lowest net global warming impact in comparison to other feedstocks such as waste concrete, steel slag, and fly ash<sup>5,9</sup>. Furthermore, using  $CO_2$  in the production of building materials can improve the strength and durability of these products<sup>10</sup>, providing an added incentive for adoption and further supporting the transition to a low-carbon economy. For this study we propose combining DAC for  $CO_2$  source and using Olivine as a feedstock for mineralization, resulting in a cement substitution, as Digula et al., 2023<sup>3</sup> showed that the Olivine based cement replacement "could replace up to 30 - 40% of conventional Portland cement. We hypothesize that the carbon emissions during conventional production of cement could be reduced by 20%-30% during the proposed process as 40% of Portland cement is replaced with the SCM considering all variables including carbon emissions during the DAC, mineralization, and

transportation. There is a significant energy requirement for DAC and compressing the  $CO_2$ , which can offset the net  $CO_2$  reduction. For the proposed method in our study we used the assumption that the DAC unit runs on renewable energy, so the environmental footprint of the unit itself is not considered, but the energy required for compressing the  $CO_2$  was considered.

## Results

Our study compares the environmental effects of the conventional cement production process with a new proposed process of producing SCM by Magnesium Silicate mineralization with  $CO_2$  captured from DAC systems. We followed the ISO guidelines to conduct a life cycle assessment (LCA) of both processes. The details of the methods and results of this LCA are described in the methods section for ease of expression.

For manufacturing of 1 ton of Portland cement in the conventional method, mining of total 1247.5 kg of raw material (table 2), requires use of 22.45 gallons of diesel resulting in 74.14 kg of  $CO_2$  emission (table 4). When added with  $CO_2$  emission required in processing of the raw material and cement production (table 5), to produce a functional unit of 1 metric ton of cement, the current conventional process releases a total of 1464.83 kg of  $CO_2$ . The proposed process replaces Portland cement with 40% SCM, emitting less  $CO_2$ , 878.90 kg, during 600 kg of Portland cement production (Table 2B, 4B and 5B). Our analysis suggests that to produce 400 kg of SCM a total  $CO_2$  emission will be 442.13 kg ( mining and processing of Olivine 1.10 kg; mineralization of Olivine 27.90 kg; DAC of  $CO_2$  5.97 kg, transportation needs 407.16 kg) while sequestering 85.61 kg of  $CO_2$  permanently (Table 6A, 6B, and 6C). The net emission in the new proposed process will be 1235.44 kg of  $CO_2$ , about 16% lower. It falls short of the hypothesized 20 - 30% reduction due primarily to the underestimated impact of transportation emissions. Despite considering the electric vehicle, transportation remains a major contributor to carbon footprint due to the volume and mass of required Olivine, the long distance involved in sourcing and delivering material.

Two big uncertainties in this experiment are the distance between sites for the proposed process, as well as the amount of cement replaced. Since the amount of cement replaced was realized from a single study, it may require further verification. Furthermore, distance between locations vary based on the country/region. Both of these, as seen in the sensitivity analysis, can change the efficiency and practicality of the proposed process (Figure 1B).

## Sensitivity Analysis

We conducted a sensitivity analysis of the 3 factors, the percent cement replaced, transportation distance, and the method of the

**Table 1** Comprehensive emission balance between conventional cement production and the proposed process.

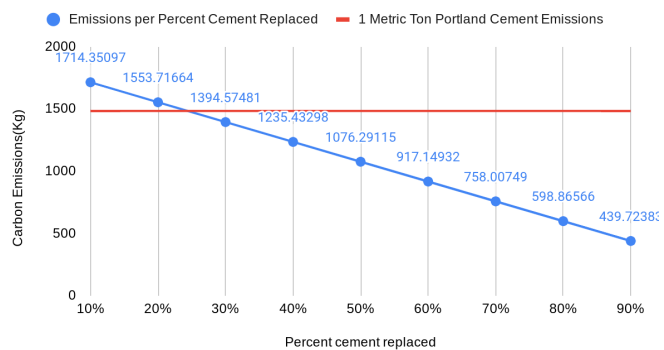
Emission Source	Portland Cement (kg CO <sub>2</sub> )	Proposed Process (kg CO <sub>2</sub> )
Raw Material Mining	74.14	1.103 (Olivine)
Cement Manufacturing	1390.7	878.89 (60% Portland Cement)
Olivine Mineralization	-	27.901
Direct Air Capture (DAC)	-	5.97
DAC CO <sub>2</sub> Sequestration (intake)	-	-85.608
Transportation	-	407.167
Total	1464.84	1235.423
Net Reduction		-229.417 kg CO <sub>2</sub>

DAC, that can have a major impact on the carbon footprint of the proposed process.

1. Percent Cement replaced

If the amount of cement replaced is changed from 40% to 50%, the CO<sub>2</sub> released during Olivine gathering increases [36.26 kg] as more Olivine is required, at the same time the sequestered CO<sub>2</sub> will increase. [107.02 kg]. Similarly, CO<sub>2</sub> released during DAC [7.46 kg] will increase, but the CO<sub>2</sub> released during cement production will decrease [670.82 kg], but the CO<sub>2</sub> released in transportation remains the same[407.167 kg]. The new amount of net carbon emissions goes from 1235.44kg CO<sub>2</sub> to 1015.04kg CO<sub>2</sub>. Similarly, if we decrease the percentage of cement replaced from 40% to 30%, due to needing 100 more kilograms of Portland cement, the amount of CO<sub>2</sub> emissions increases to roughly 1,437 Kg per ton of cement produced. The figure 1A shows the linear relation between the percent of cement replaced and the net CO<sub>2</sub> released. Our analysis suggests that the proposed process is only feasible, primarily from the environmental perspective, when the amount of cement replaced is at least 25%. If it drops below that, the proposed process will release more emissions than conventional cement production.

Carbon Emissions(Kg) vs. Percent cement replaced



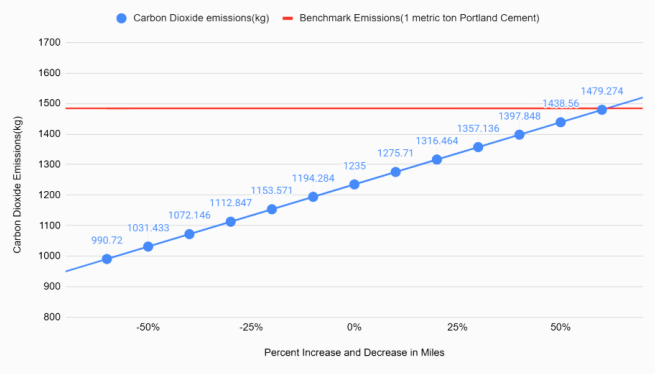
**Figure 1A.** Effect of varying cement replacement percentages on carbon emissions (kg)

**Figure 1A.** The relation between percent of cement replaced (x axis) and CO<sub>2</sub> emissions in kilograms(y axis). The red line depicts the CO<sub>2</sub> emissions associated with conventional cement production.

2. Transportation change:

The number of miles driven can also greatly affect the amount of CO<sub>2</sub> released. The comparison of CO<sub>2</sub> emissions between changing the percent of miles driven and the percent of cement replaced is shown in Figure 1B.

Carbon Dioxide emissions(kg) vs. Percent Change in Miles



**Figure 1B.** The relation between percent change in miles traveled (x axis) and CO<sub>2</sub> emissions in kilograms(y axis). The red line depicts the CO<sub>2</sub> emissions associated with conventional cement production.

3. DAC method change

Here we describe sensitivity analysis using an alternate DAC method. The Fresnel+PV system is an integrated, autonomous off-grid solution designed to support DAC operations entirely through solar energy. This system combines two technologies: Fresnel solar collectors, which provide high-temperature heat up to 400°C, and PV panels,

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which generate electricity. The system is equipped with storage media heat storage tanks and batteries to mitigate the intermittency of solar energy, ensuring continuous DAC operation by maintaining a steady supply of electricity and heat. Fresnel solar collectors, particularly effective for industrial processes requiring high temperatures, generate steam that is used in the desorption stage of  $CO_2$  capture, which operates at around  $100^\circ C$ . It enables the capture of 100,000 tons of  $CO_2$  annually from the ambient air, offering a renewable, sustainable approach to carbon capture<sup>11</sup>. This process, since it needs heating, will release more  $CO_2$  than the method in the proposed process. This process will add another 75 kg of  $CO_2$ , making our total emissions 1310.44 kg of  $CO_2$ . This number is derived as the Fresnel+PV system needs 1500 kilowatts of electricity generated by solar panels, which release about 50g  $CO_2$  per kWh.

According to the LCA guidelines highlighted in Michigan University's Assess CCUS, this proposed process technically cannot be determined to have negative emissions of 85.612 kg  $CO_2$ , as this is a cradle to gate LCA, which the guidelines states is not sufficient to determine negative emissions. Although the  $CO_2$  is permanently fixated in the cement, the carbon captured, and carbon negated, are classified as environmental benefits including a reduction of 315 kg of  $CO_2$  emission for every metric ton of cement produced. According to these guidelines our emissions would not count subtracting the 85.61 kg from the Direct Air Capture, resulting in emissions of 1321.05 kilograms, however in the results and sensitivity analysis the amount captured by DAC was subtracted assuming they would stay negative emissions in a cradle to grave study.

These guidelines were selected for their transparent handling of carbon flows in CCUS processes and their relevance to evaluating engineered carbon storage and material substitution. While other LCA methodologies such as ISO 14044 or Ecoinvent may differ in their treatment of temporary carbon storage, substitution credits, or system expansion, the Michigan framework offers a consistent and context-appropriate basis for assessing the climate impact of this DAC-olivine cement pathway under cradle-to-gate conditions. These assumptions are explicitly stated to ensure transparency and facilitate comparison across LCA approaches.

## Discussions

In this study,  $CO_2$  emissions from normal cement manufacturing to 60% Portland cement and 40% cement replacement made from Olivine which underwent a mineralization process using  $CO_2$  from a DAC unit as a feedstock is compared. Beginning

with gathering the raw materials from the quarry, and then calculating the carbon emissions of each of the machines used in this process. After factoring in the transportation to the cement plant the emissions of each machine used in the process of converting the raw materials to cement was found. Similarly, the amount of  $CO_2$  emissions from mining Olivine and found the amount of  $CO_2$  emitted during the mineralization process was gathered. Then finding what type of DAC unit, the data was gathered on its energy use and  $CO_2$  emissions. Transportation between all units was considered as necessary.

When contextualized against the proposed solution of integrating  $CO_2$  capture with mineralization, the advantages and challenges become clear. The combination of  $CO_2$  capture with mineralization provides a compelling solution by achieving permanent sequestration of  $CO_2$  while creating valuable byproducts. However, the scalability of mineralization is often limited by the availability of suitable waste materials and the energy requirements of the process. In contrast, DAC technologies, like those used by ClimeWorks and CarbonCapture, offer flexibility in terms of location and the ability to capture  $CO_2$  directly from the air, yet they are currently constrained by high costs and energy demands. CarbonCures approach of integrating  $CO_2$  into existing industrial processes provides a more immediate and cost-effective solution but is limited by the market demand for the specific products it creates. Ultimately, the choice of technology will depend on the specific needs of industries, geographic considerations, and economic factors, with each approach offering unique strengths and facing distinct challenges in the effort to combat climate change.

The sensitivity analysis shows that as technology further develops in this field of DAC, there is much room for improvement. The amount of cement that can be replaced with Olivine that underwent the mineralization process is increased, the more efficient and useful this proposed process could be. Although when changing the method of DAC the amount of  $CO_2$  emissions went up, there are definitely areas in which improvement is possible. The DAC unit proposed captures 100kt $CO_2$ /year, but this number will continue to improve as the learning curve further heightens. Also, not factored in was what happens after the 20-year lifetime of the DAC plant and maintenance on it which could contribute to higher  $CO_2$  emissions. Transportation can be an issue however, with the concentration of these environmental facilities is not high in any specific area, transportation can be something which lessens the feasibility of the process as distance between sites increases. The sensitivity analysis also leads to the conclusion that our output, although sensitive to both cement replaced and miles driven, is more sensitive to the amount of cement replaced. (Figure 1A and 1B)

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## Comparisons:

CarbonCure Technologies stores approximately 4-6kg of  $CO_2$  per metric ton of concrete produced. This process involves injecting captured  $CO_2$  into the concrete mix, where it mineralizes and becomes permanently trapped as calcium carbonate. Although this seems like an extremely low number, more  $CO_2$  is captured and prevented as the concrete cures, and storing  $CO_2$  reduces the amount of cement needed. On the other hand, Blue Planet's approach is different, focusing on creating synthetic limestone aggregates from captured  $CO_2$ . Blue Planet's process can store significantly more  $CO_2$  up to 440 kg per metric ton of aggregate used in concrete. While CarbonCure's method stores a smaller amount of  $CO_2$  directly in the concrete mix, Blue Planet stores a much larger quantity through the aggregate, making their approach potentially more impactful in terms of  $CO_2$  storage per ton of concrete material. Our proposed process compares decently with both of them, storing around 85kgs and preventing another 229.39 kgs. It is important to note that the technology used in this proposed process is at a lower Technology Readiness Level (TRL), very likely to continuously improve with time. . If the need for transportation decreases then a good amount of emissions can be reduced. Furthermore, if found that more than 40% of cement can be replaced without integrity being compromised, as shown in the sensitivity analysis, this process can prove even further efficient.

## Scale up:

The potential for scaling up DAC systems is promising and could lead to improved Technology Readiness Levels (TRLs). Co-locating the DAC unit, mineralization unit, and olivine mine ideally within the same facility could significantly reduce  $CO_2$  emissions associated with transportation. Accessing olivine is relatively straightforward, as it makes up over 50% of the Earth's upper mantle and is already mined at several major sites in the U.S., with the largest located in Washington and others in North Carolina, Georgia, and Montana. Therefore, olivine availability is unlikely to be a limiting factor in large-scale deployment.

However, scaling up DAC for supplementary cementitious material (SCM) production requires highly efficient DAC and compression systems, and several factors may act as constraints. One key requirement is access to renewable energy. While this could be a challenge, the rapid expansion of renewable technologies coupled with sufficient funding should make this more feasible at scale. That said, large-scale DAC also demands a  $CO_2$  pipeline network comparable in scope to today's natural gas infrastructure. Constructing such infrastructure is capital intensive, as are alternative options like  $CO_2$  trucking or shipping. Public opposition to dedicating large tracts of land for DAC facilities may further complicate deployment. Additionally, specialized components such as fans, compressors, and vacuum pumps are costly, have long lead times, and contribute to overall

capital intensity. Carbon pricing remains too low to drive significant private-sector investment, and voluntary carbon markets alone cannot sustain the gigaton-scale  $CO_2$  removal needed to reach net-zero targets by 2050. Likely a substantial government intervention through mandates or large-scale subsidies can bridge this gap.

## Economic Viability:

While this study may be feasible in terms of carbon emissions, it is important to consider the economic implications. Producing one ton of cement typically costs around \$160. In comparison, our proposed process not only maintains this production cost but also incurs additional expenses for  $CO_2$  capture and carbonation. The cost of carbon capture varies significantly depending on the source and technology used. For industrial processes with pure  $CO_2$  streams, costs range from 15 to 25 per ton. For processes with dilute gas streams, such as cement production, costs range from 40 to 120 per ton. While the mineralization of olivine costs may vary on multiple factors it is estimated around \$100 per ton. In our process, as detailed in the methods, only 85 kg of  $CO_2$  is captured per ton of cement, requiring about 250 kg of olivine. Consequently, the total cost rises to approximately \$35 per ton of cement - a 22% increase, which may impact feasibility. However, as direct air capture and mineralization technologies advance, their costs are expected to decline.

## Study Limitations:

The data used in this study were sourced from peer-reviewed publications that provided detailed experimental and modeling information relevant to each stage of the CCS process. While studies were selected based on their relevance, methodological rigor, and recency to ensure an accurate representation of current technologies and practices, we acknowledge the potential for selection bias, which may have influenced the outcomes of our analysis. The assumption of a 40% cement replacement is based on a single study and may not be universally applicable. Broader validation across varying conditions and cases is needed to confirm the generalizability and practical feasibility of this approach. Olivine mineralization processes can vary significantly in terms of efficiency, energy requirements,  $CO_2$  storage capacity, and emissions, depending on the method employed such as direct aqueous carbonation, utilization of mine tailings, or enhanced weathering, and our study does not fully capture this variability. Additionally, our analysis does not account for emissions associated with the maintenance or decommissioning of DAC plants beyond their assumed 20-year operational lifespan. These factors could contribute additional carbon costs that are not reflected in the current assessment. As outlined in our general assumptions, the direct air capture (DAC) process is modeled using energy supplied by solar power. However, our analysis

does not account for the life cycle emissions embedded in the production, installation, and maintenance of solar panels, energy storage systems (e.g., batteries), and associated infrastructure.

Finally, economic impact and cost analysis are outside the scope of a standard Life Cycle Assessment (LCA). As such, we did not compare the economic feasibility of the proposed process with conventional methods or with alternatives such as Carbon-Cure or Blue Planet. While we recognize that cost-effectiveness is crucial for large-scale, real-world implementation, this study focuses solely on evaluating the environmental performance of the proposed approach and does not address its financial viability.

## Materials & Methods:

### International Organization of Standardization (ISO) Standards

ISO 14044 provides detailed guidelines that build on the general framework outlined in ISO 14040 to ensure accuracy and consistency in Life Cycle Assessment (LCA). We followed ISO guidelines for this study and per guideline have described a clear and transparent explanation of the study's objective, its intended application, and the functional unit, define system boundaries and detail assumptions, limitations, and exclusions. Further ISO 14044 guidelines were followed for Life Cycle Inventory (LCI) Analysis, Life Cycle Impact Assessment (LCIA), and interpretation as well as reporting of our study findings.

### Methodology

This study analyzed the practicality of DAC and mineralization while using Olivine as a feedstock. This approach not only ensures the permanent sequestration of  $CO_2$  but also generates a cement replacement, further lowering the carbon dioxide emissions of the cement production industry. The study findings can add to the literature aimed at reducing emissions in the cement manufacturing process. The results may provide insights into potential modifications to the production process that could lower costs and minimize environmental impacts.

### General Assumptions:

- The Magnesium Silicate cement substitute can replace 40% of Portland cement without compromising strength or integrity.
- The functional unit of 1 metric ton of cement (60% Portland cement, 40% substitute) is comparable to traditional Portland cement in performance.
- Data from external sources are representative of real-world operations.

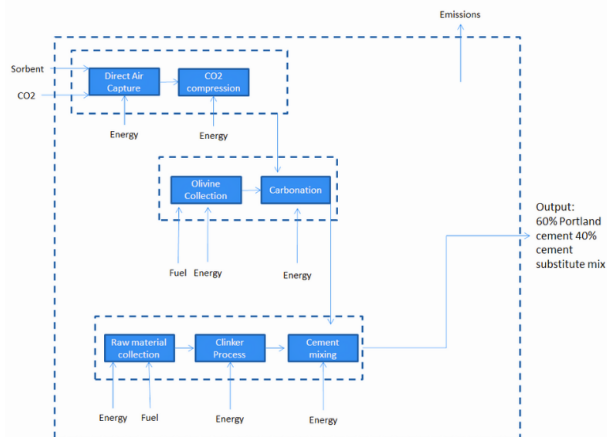
- DAC and mineralization processes are at low Technology Readiness Levels (TRL) but can be scaled up for analysis.
- The LCA focuses on a cradle-to-gate scope, excluding usage, maintenance, and end-of-life stages.
- Emission reductions are based on replacing traditional cement processes with DAC and Magnesium Silicate mineralization.

### Functional unit

The product of the mineralization will be assumed to be identical to cement, and will be integrated with Portland cement<sup>9</sup>. Therefore, the functional unit will be 1 metric ton of cement produced comparing 1 metric ton of regular Portland cement with 1 metric ton made of 40% Olivine-based cement substitute and 60% Portland cement.

### System Boundaries (Figure 2)

Our study proposes the following process: Through Direct Air Capture,  $CO_2$  will be captured, compressed, and sent to the mineralization plant. At the mineralization plant Olivine (Magnesium Silicate), will be mined, processed, carbonated, and processed to produce a cementitious substitute. This will be transported to the cement plant where the cement and the substitute will be mixed, so the cement substitute replaces 40% of the total amount of material produced, which originally would have been cement.



**Figure 2.** The system boundary and process flow of the proposed process

### Life Cycle Inventory (LCI)

The data collected from peer-reviewed publications provided detailed experimental and modeling data relevant to each stage of the CCS process, including carbon capture, compression, mineralization, and transport. The studies were selected based on their relevance, methodological rigor, and recency to ensure accurate representation of current technologies and practices.

**Primary Data Sources:** Comprehensive review of recent peer-reviewed publications that reported on operational data from the pilot and commercial-scale CCS facilities were used as primary data source for LCI.

**Secondary Data Sources:** Additional background data required for upstream processes (such as the production and transportation of amine solvents, natural gas extraction, and electricity generation) were obtained from secondary sources, including data repositories like the U.S. Life Cycle Inventory Database and the Environmental Protection Agency. These databases were used to supplement the primary data with information on upstream processes and background emissions, ensuring a comprehensive Life Cycle Inventory (LCI).

The data from research papers were extracted systematically, with emphasis on parameters most critical to the LCA outcomes. Where possible, data were averaged or normalized to the defined functional unit to maintain consistency across different studies. Variability in reported values was addressed by selecting the most representative figures.

**Raw Material Assumptions:**

- Sufficient quantities of Olivine and other raw materials are available and economically sustainable.
- Equipment efficiency for material extraction and processing matches referenced values.
- Material densities (e.g., limestone, gypsum, Olivine) are accurate and consistent.

**Process-Specific Assumptions:**

- The DAC system uses renewable energy sources (e.g., solar PV) with no direct emissions except for CO<sub>2</sub> compression.
- Energy consumption for DAC compression is constant across scenarios.
- Mineralization efficiency and CO<sub>2</sub> storage capacities follow referenced study values.
- Water and energy demand for mineralization are constant and achievable with current technologies.
- Fixed conversion factors are used for CO<sub>2</sub> emissions per megajoule (MJ) of energy, based on EPA data.

**Conventional Cement production process**

Limestone, iron ore, shale (or sand), and gypsum are essential raw materials in cement production, each contributing unique properties to the final product. Using the functional unit of 1 metric ton of cement, and using ratios highlighted in an LCA of cement production<sup>12</sup>, the amounts of raw material needed were calculated as described in Table 1A.

**Table 2A.** Amount of raw material required in production of 1 metric ton of Portland cement

Materials	Quantity(kg)
Limestone	1150
Iron Ore	7.5
Shale/Sand	40
Gypsum	50

Table 2A: The quantities in kilograms of the necessary raw materials in producing 1 metric ton of Portland cement which was gathered through corroborating information throughout available credible data.

Limestone, the primary ingredient, provides calcium carbonate, which decomposes during calcination to produce lime (calcium oxide), a key component of clinker. Iron ore is included to supply iron, which helps to enhance the strength and durability of the cement by influencing the formation of certain compounds during the clinkerization process. Shale or sand acts as a source of silica and alumina, which are vital for the development of the cement’s hydraulic properties and ensure proper binding characteristics. Lastly, gypsum is added to regulate the setting time of cement, preventing rapid hardening and allowing for manageable workability. Together, these materials create a balanced and effective composition, resulting in high-quality cement with desirable mechanical and physical properties.

Per hour efficacy and fuel consumption of different machineries for mining of each raw material was collected as described in table 3<sup>13</sup>.

**Table 3:** Productivity and fuel use per machine per hour in mining of raw materials

Machine	Limestone m3/hour	Shale/Sand m3/hour	Gypsum m3/hour	Fuel use gal/hour
Excavators	100	100	100	5
Bulldozers (700hp)	240	582	362.88	29
Front end Loaders	27.7	27.7	27.7	3

Table 3. Machines used to excavate raw material, and their productivity alongside their fuel use per hour.

Further Amount of fuel consumed and CO<sub>2</sub> emitted in mining of raw materials required to produce 1 metric ton of cement was calculated and described in table 4A. (For example, the density of limestone is 2100 kg/m<sup>3</sup> ( meaning 100m<sup>3</sup> would be 210000 kg. If this value is divided by 182.61 kg, 1150 kg of limestone required is reached. Similarly, when the 5 gallons of fuel is divided by the same value, 0.027 gallons used in the excavator per 1150 kilograms of limestone is calculated. Similarly, using densities of 1600 kg/m<sup>3</sup> for shale/sand and 1282 kg/m<sup>3</sup> for gypsum, the amount of fuel used to collect the necessary amount of material was calculated. The amount

of  $CO_2$  released was found by using the conversion factor of 22.45 gallons of diesel resulting in 74.14 kg of  $CO_2$  emitted (Information from the Environmental Protection Agency (EPA)). [Table 4A].

Table 4A. Amount of fuel consumed and  $CO_2$  emitted in mining raw materials per machine

Machine	1150 kg Limestone		40 kg Shale/Sand		50 kg Gypsum	
	Fuel (gal)	$CO_2$ (kg)	Fuel (gal)	$CO_2$ (kg)	Fuel (gal)	$CO_2$ (kg)
Excavators	0.027	0.089	0.0013	0.0041	0.002	0.0064
Bulldozers (700hp)	0.066	0.21	0.003	0.0099	0.0031	0.01
Front end Loaders	0.059	0.19	0.0027	0.0089	0.0042	0.014

Table 4A. The amount of fuel used and  $CO_2$  emitted in mining of raw material required to produce 1 metric ton of Portland cement

We were unable to retrieve sufficient or reliable data from published literature to allow similar calculations for Iron ore. For the amount of iron ore needed 0.6447 MJ is required<sup>14</sup>. LCA<sup>12</sup> shows  $CO_2$  emission for mining 7.5 kg iron ore to be 0.13 kg.

After collection these raw materials are sent to the Jaw Crusher, which consumes 3.438 MJ/metric ton of cement while crushing the raw materials. After that Iron ore and Gypsum are added. These processed materials then are sent to the raw mill where materials are dried and crushed into a fine powder. The mix is then transferred to the preheater, where the materials are being heated in preparation for the rotary kiln. In the rotary kiln, materials are burned at a temperature of around 1500 degrees Celsius to produce clinker, then cooled down in a grate cooler. After the clinker is stored in a silo, gypsum and limestone are added to the clinker. This mix is then sent to cement mills, finally, being bagged.

Table 5A. The energy needed and  $CO_2$  emissions per machine needed during cement manufacturing in chronological order to make 1 metric ton of Portland cement.

Machine	Energy (MJ/ton)	$CO_2$ emitted (kg)
Jaw Crusher	3.44	0.67
Raw mill	72	13.97
5 stage cyclone pre-heater	3010	583.94
Rotary Kiln	4000	776
Grate Cooler	310.32	60.2
Vertical roller Mill	136.44	26.47
Cement bagging	15	2.91

Table 5A shows the machines used in processing the raw material and cement production in chronological order along with the

amount of energy used in each machine and  $CO_2$  emitted (0.194 kg  $CO_2$ /MJ) to produce 1 metric ton Portland cement<sup>15-20</sup>.

**Total amount of  $CO_2$  released: 1464.84 kg per Metric Ton of Cement**

### Proposed Cement production Process

In the proposed process the cement substitute will replace 40% of the 1 ton of Portland cement and will require production of 600 kg cement.

Table 2B. The amount of raw materials needed for the production of 600 kg of Portland cement to be used alongside 40% SCM in the proposed process

Materials	Quantity(kg)
Limestone	690
Iron Ore	4.5
Shale/Sand	24
Gypsum	30

Table 2B: The quantities in kilograms of the necessary raw materials in producing 600 kg of Portland cement which was calculated by taking 60% of the values in table 1A.

Table 4B. Amount of fuel consumed and  $CO_2$  emitted in mining raw materials per machine

Machine	690 kg Limestone		24kg Shale/Sand		30kg Gypsum	
	Fuel (gal)	$CO_2$ (kg)	Fuel (gal)	$CO_2$ (kg)	Fuel (gal)	$CO_2$ (kg)
Excavators	0.016	0.053	0.0008	0.0025	0.0012	0.0039
Bulldozers (700hp)	0.039	0.13	0.0018	0.0059	0.0018	0.0061
Front end Loaders	0.035	0.12	0.0016	0.0054	0.0025	0.0083

Table 4B. The amount of fuel used and  $CO_2$  emitted in mining of raw material required to produce 600 kg of Portland cement for the proposed process with SCM

Table 5B. The energy needed and  $CO_2$  emissions per machine needed during cement manufacturing in chronological order to make 600 kg of Portland cement.

Therefore, the amount of raw material needed [Table 1B], the fuel consumed and  $CO_2$  emitted during mining the same [Table 3B], and the energy consumed and  $CO_2$  emitted in manufacturing of 600 kg Portland cement [Table 4B], will be 60% of the respective values in the benchmark conventional cement production process<sup>15-20</sup>. Based on LCA<sup>12</sup>  $CO_2$  emission of mining 4.5 kg iron ore to be 0.075 kg.

**Total amount of  $CO_2$  released: 878.90 kg per 600 kg Portland cement**

### SCM Manufacturing Process:

The first step is gathering the Olivine. According to Digulla et al., 2023<sup>3</sup>, from every 1 kg of Olivine, 1.45 kg of cement

Table 5B. Amount of energy used and CO<sub>2</sub> emitted in manufacturing 600 kg of Portland cement

Machine	Energy (MJ/ton)	CO <sub>2</sub> emitted (kg)
Jaw Crusher	2.06	0.4
Raw mill	43.2	8.38
5 stage cyclone preheater	1086	350.36
Rotary Kiln	2400	465.6
Grate Cooler	186.192	36.12
Vertical roller Mill	81.864	15.88
Cement bagging	9	1.75

substitute is made. Therefore, to replace 40%, or 400 kg, of Portland cement, 275.86 kg of Olivine is required. The machines and values calculated to extract Olivine [Table 6A] are estimated relative to the amounts needed for gathering limestone as their densities are proportional<sup>13,17</sup>. Through the same mathematical processes used earlier, the amount of fuel consumption and CO<sub>2</sub> emissions in gathering Olivine were calculated and described in Table 6B. Next the Jaw Crusher crushes the raw Olivine into smaller parts which are easier to transport. By converting the factor of 3.438MJ used per metric ton processed in the Jaw crusher<sup>14</sup>, the amount of energy needed and CO<sub>2</sub> emitted for processing 275.86 kg of Olivine are calculated and described in table 6C.

Table 6A. Productivity and fuel use per machine per hour in mining of Olivine for SCM

Machine	Olivine m <sup>3</sup> /hour	Fuel use gal/hour
Bulldozers	500000	29
Loaders	50000	5
Excavators	250000	5

Table 6A. The quantities in kilograms of the necessary raw materials in producing 1 metric ton of Portland cement which was gathered through corroborating information throughout available credible data.

Table 6B. Amount of fuel consumed and CO<sub>2</sub> emitted in mining Olivine per machine

Machine	275.86 kg Olivine	
	Fuel (gal)	CO <sub>2</sub> (kg)
Bulldozers	0.015	0.053
Loaders	0.028	0.091
Excavators	0.0055	0.018

Table 6B. The amount of fuel used and CO<sub>2</sub> emitted in mining

of raw material required to gather 275.86 kg Olivine to produce 400 kg SCM

Table 6C. Amount of energy used and CO<sub>2</sub> emitted in processing 275.86 kg Olivine

Machine	Energy (MJ/ton)	CO <sub>2</sub> emitted (kg)
Jaw Crusher	0.95	0.18
Cone Crusher	0.018	0.061
Ball Mill	3.63	0.7

Table 6C. The energy needed and CO<sub>2</sub> emissions per machine needed during olivine processing in order to make 400 kg of Olivine based SCM

Before mineralization the Olivine needs further grinding to make fine particles at sub-micron level and increase surface area through ball mill. Using the references of cone crusher efficiency 10 gallons of fuel/150 Tons<sup>21</sup>, and ball mill efficiency as 90MJ/Ton<sup>22</sup>, the energy consumed and CO<sub>2</sub> emitted in processing 275.86 kg of Olivine was calculated and described in Table 5C.<sup>14,21,22</sup>

**Total amount of CO<sub>2</sub> released: 1.103 kg during mining and processing of Olivine to produce 400 kg of SCM or 1 metric ton of cement in the proposed process.**

The final phase is the mineralization. The amount of carbon dioxide stored in magnesium, the amount of energy needed, and the amount of water used are known. It is known that 0.45 kg CO<sub>2</sub> is stored per 1.45 kg of the SCM. This process takes 0.21 kWh of energy<sup>3</sup>. The amount of CO<sub>2</sub> stored per 1.45 kg of Olivine is 0.45 kg CO<sub>2</sub>, and the amount of energy needed to complete mineralization of 1.45 kg Olivine is 0.21 kWh<sup>3</sup>. To produce 400 kg of SCM, 275.86 kg of Olivine is needed. Therefore, in the production of 400 kg SCM 85.61 kg CO<sub>2</sub> is mitigated or stored, at the expense of 39.95 kWh energy and emission of 27.901 kg CO<sub>2</sub>(kWh to MJ to CO<sub>2</sub>).

**Total amount of CO<sub>2</sub> released: 27.901 kg during mineralization of Olivine to produce 400 kg of SCM per metric ton in the proposed process.**

**Total amount of CO<sub>2</sub> stored or mitigated: 85.612kg during mineralization of Olivine to produce 400 kg of SCM**

#### Direct Air Capture (DAC)

For DAC we propose carbon capture and compression using a near future design of a system which can capture and compress 100kt (kiloton) of CO<sub>2</sub> per year<sup>11</sup>. This system is an autonomous, off-grid, all-electric setup designed to capture CO<sub>2</sub> using direct air capture technology. It is powered entirely by photovoltaic (PV) panels, which supply electricity to a high-temperature heat pump (HTHP) that provides the necessary heat for the CO<sub>2</sub> capture process. The HTHP delivers heat at 100°C, which is required for efficient CO<sub>2</sub> capture. Nickel Manganese Cobalt (NMC) batteries with large capacity are used during

nighttime to conserve energy due to the high electricity demand of this method<sup>11</sup>.

Gathered from an LCA of the proposed DAC method<sup>11</sup>, a system which captures 100kT  $CO_2$  per year and is operational for 20 years, will require 1132 kWh/t $CO_2$ . Since the plant runs on solar power, it is assumed that no  $CO_2$  is released in the energy needs for capturing  $CO_2$ . But for compressing the  $CO_2$ , 360MJ are needed per ton<sup>11</sup>, and as this is not done at the DAC unit, it will release  $CO_2$ . Therefore, we calculated the amount of energy required to compress 85.612kg  $CO_2$  as that is the amount which is stored in the Olivine during mineralization. Using these calculations, DAC of  $CO_2$  required to manufacture 400 kg of SCM, will need 30.8203 mJ energy and will release 5.97kg of  $CO_2$ .

**Total amount of  $CO_2$  released: 5.97 kg per Metric Ton of Cement**

**Total amount of  $CO_2$  captured: 85.612kg per Metric Ton of Cement**

### Transportation

#### Transportation Assumptions

- Average transportation distances (e.g., 5 miles from quarry to cement plant) are fixed and representative.
- All materials are transported using electric semi-trucks with specified energy consumption rates.

#### Proposed Process transportation

The transportation in the scope of this process is highlighted below: Raw materials from quarry to cement plant, Olivine to mineralization plant, DAC plant to mineralization plant, and finally Mineralization plant to cement mixing plant. For calculating the transportation, the following assumptions are made : Raw materials will come from a quarry 5 miles from the cement plant The cement plant will be the Ste Genevieve Holcim cement plant in Missouri The Olivine will come from the Burnsville mines in Yancey County, North Carolina The CCS plant will be the plant in Decatur Illinois The DAC plant will be a new plant on Charles Mound in Illinois.

The reason for picking the cement plant's location was because of the size of it, giving more base to the assumption it is able to produce the cement and mix it with the substitute on a large scale. The Olivine plant was the one which is closest to the Cement plant which produces a large amount of Olivine yearly. The CCS plant was one which is semi-functional and is close to the cement plant, and the DAC plant will be built on a close and assumed feasible area. The amount of energy used and  $CO_2$  released during transportation is described in [Table 7], assuming to have been transported in a semi electric truck(uses 3.6 MJ of energy per mile).

Table 7. The number of miles, MJ, and  $CO_2$  released per area of transportation. Conversion factor of MJ to  $CO_2$  is the same as

Table 7.  $CO_2$  released in transportation of materials between sites

	Miles	MJ	$CO_2$ kg released
Raw material s to cement plant	5	18	3.492
Burnsville mines to CCS site	150	540	104.76
DAC to CCS site	248	892.8	173.203
CCS site to Cement plant	180	648	125.712

what has been used throughout the paper. (CCS-Carbon Capture Storage) (DAC-Direct Air Capture).

Assuming each truck is at full capacity, which is 82000 kg, then the amount of MJ for each process is 82000 kg divided by the amount of material needed for 1 metric ton of cement, which is then multiplied by the amount of MJ per mile times the miles. As a reminder, the amount of materials needed for the proposed process is 744 kg of raw material from the quarry to the cement manufacturing plant, 275.86kg of raw Olivine, 85.612kg of compressed  $CO_2$ , and 400 kg of cement replacement.(**Total  $CO_2$  released: 407.167) Proposed process net  $CO_2$  emissions: 1235.43kg**

### Conclusions:

The proposed process shows significant environmental benefit over a conventional cement production by reducing about 229.39 kg  $CO_2$  emission and 85kg of negative emissions. This process has a very high likelihood of improving over the next decades with more research and attention to these fast evolving technologies. Evolution of emerging technologies such as DAC and mineralization can help achieve the net zero goal by 2050.

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