Sequestration of Carbon Dioxide via Mineral Carbonation to Produce Magnesium Carbonate: A Design Study

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The rapid increase in atmospheric carbon dioxide (CO_2) due to industrialization and fossil fuel combustion has raised significant concerns about global warming. Carbon capture and storage (CCS) is a crucial technology for reducing greenhouse gas (GHG) emissions. This study presents the design of a mineral carbonation plant capable of sequestering 30 tons of CO_2 per day to produce magnesium carbonate ($MgCO_3$) using olivine as the feedstock. The process follows an ex-situ carbonation approach, where a mineral slurry reacts with CO_2 under controlled conditions. The plant design includes the development of key equipment such as a reactor, heat exchanger, and flash column, with a detailed process flow diagram (PFD) modeled in Aspen Plus. Material and energy balances ensure the operational feasibility of the system.

With an effective conversion rate of 50%, the process accounts for realistic industrial limitations while maintaining reliability at scale. Heat recovery mechanisms, including a shell-and-tube heat exchanger, improve energy efficiency by minimizing heat loss. Optimized equipment design ensures process scalability and aligns with performance criteria to meet sequestration targets and product quality standards.

The reliance on olivine, an abundant and cost-effective silicate mineral, highlights the economic and environmental advantages of this approach. The findings contribute to advancing sustainable CCS technologies, offering a viable solution for CO_2 mitigation while producing valuable industrial products such as $MgCO_3$ and by-product SiO_2.

Keywords: Mineral Carbonation; Olivine; Magnesium Carbonate; and Ex-Situ Carbonation.

Introduction:

The global rise in CO_2 emissions from fossil fuel consumption is a major driver of climate change [1]. Addressing this challenge requires innovative carbon capture and storage (CCS) technologies. To stabilize atmospheric CO_2 at approximately 500 ppm by 2050, a broad portfolio of solutions is needed, with CCS recognized as a flagship technology for transitioning from a fossil fuel-based economy to a renewable-based one [2]. CCS encompasses various processes that capture CO_2 from power plants, cement factories, steel production, and natural gas treatment, preventing its release into the atmosphere [3]. All pathways to limiting global warming to 1.5°C rely on some form of CO_2 removal, with an estimated 190 Gt of CO_2 needing to be stored [4]. However, large-scale CCS deployment remains a challenge, requiring significant technological advancements.

Among CCS methods, mineral carbonation has gained attention as a promising long-term solution due to its ability to permanently store CO_2 in the form of stable carbonates. Unlike geological or ocean storage, which requires extensive monitoring and poses leakage risks, mineral carbonation mimics natural rock weathering, converting CO_2 into magnesium and calcium carbonates [5]. These carbonates can be used in industrial applications or safely stored. Studies identify olivine (Mg_2SiO_4) as a particularly effective mineral due to its high magnesium content, abundance, and fast reaction kinetics compared to other silicates.

Despite its potential, large-scale mineral carbonation faces challenges, including high energy consumption, slow reaction kinetics due to passivation layer formation, and CO_2 supply chain constraints. Research has explored mechanical activation, acid leaching, and thermal pre-treatment to improve efficiency, but economic feasibility and process optimization remain key concerns. Additionally, while mineral carbonation has been extensively studied in industrial regions, its implementation in Pakistan remains underexplored. Given the presence of ultramafic rock deposits rich in olivine, Pakistan has significant potential for localized CCS solutions.

This study aims to develop a scalable CO_2 sequestration process using locally available olivine, integrating material and energy balance considerations to enhance process efficiency. By addressing key technical and economic barriers, this research contributes to advancing sustainable CCS technologies for long-term climate mitigation.

Novelty Statement:

This study presents the design of a mineral carbonation plant capable of sequestering 30 tons/day of CO_2, producing valuable industrial products such as magnesium carbonate ($MgCO_3$) and silica (SiO_2) while minimizing cost, energy consumption, and environmental impact. The proposed ex-situ carbonation process utilizes olivine with minimal pre-treatment, efficient heat recovery mechanisms, and precision-engineered equipment to enhance efficiency and sustainability. Unlike conventional methods, this system achieves a high sequestration rate while ensuring economic viability through the production of commercially valuable by-products.

Sustainable Development Goals:

This study aligns with the following United Nations Sustainable Development Goals (SDGs):

- **SDG 9:** Industry, Innovation, and Infrastructure – by promoting advancements in carbon capture technology.
- **SDG 11:** Sustainable Cities and Communities – by contributing to cleaner industrial processes and reduced emissions.
- **SDG 13:** Climate Action – by mitigating CO_2 emissions through effective sequestration strategies.

Objectives of the Study:

- **Design a process flow** for an aqueous olivine carbonation plant to sequester CO_2.
- **Calculate mass flow rates** and analyze energy requirements for efficient process integration.
- **Design key equipment** essential for the carbonation process.
- **Evaluate mineral carbonation** as a practical and sustainable method for CO_2 sequestration.

Literature Review:

Carbon Capture and Storage (CCS) technology aims to prevent CO_2 emissions from entering the environment, thus reducing the carbon footprint. There are three major CCS methods: Geological Storage, Ocean Storage, and Mineral Carbonation[5].

1. **Geological Storage** involves injecting captured CO_2 into specific geological formations, such as coal-bed formations or depleted oil and gas reservoirs[6]. The rationale behind injecting CO_2 into these reservoirs is that the hydrogeological conditions that originally allowed hydrocarbons to accumulate also enable CO_2 to be stored. As long as the caprock remains intact (unexposed, undamaged, and not weakened by excessive pressure), it can trap CO_2 for thousands of years[7].
2. **Ocean Storage** refers to injecting CO_2 into deep ocean layers, either in liquid or gaseous form. The ocean, with a residence duration of several hundred years, acts as the largest accessible sink for CO_2[8]. The deep ocean's thermocline stratifies its layers, which slowly mix over time, facilitating CO_2 sequestration. At depths above 1500 meters, CO_2 can be injected as a liquid or trapped as hydrates, or it may dissolve in the water column[9].
3. **Mineral Carbonation** is a promising CCS technology in which CO_2 reacts with silicate minerals like olivine or serpentine to form stable carbonates such as $MgCO_3$ and $CaCO_3$[10]. This method not only sequesters CO_2 but also captures and utilizes it to produce valuable industrial products like magnesium carbonate, giving it an edge over other CCS methods[5].

In Pakistan, where rapid demographic growth and industrialization heavily depend on fossil fuel consumption, CO_2 emissions are becoming a growing environmental concern[11]. This highlights the urgent need for implementing CCS technologies. The objective of this study is to design a mineral carbonation plant that sequesters CO_2 emissions from fossil fuel combustion through the mineralization of olivine. It is found that when olivine reacts with water, a strong passivating layer forms, significantly trapping CO_2 from the atmosphere[12]. The focus of this study is to develop an efficient process that minimizes the need for pre-treatment, particularly addressing the shedding of the passivation layer to make the carbonation process more economical.

There are two primary types of mineral carbonation processes: In-situ and Ex-situ.

- **In-situ carbonation** occurs naturally by injecting CO_2 into silicate-rich geological formations or alkaline aquifers, targeting minerals like peridotite and basalts[13].
- **Ex-situ carbonation** takes place in a controlled environment, typically in a chemical processing plant after the mineral has been mined. This process uses a slurry of minerals like olivine, which is then reacted with compressed CO_2 to form useful products like magnesium carbonate[14].

For this study, ex-situ carbonation is chosen because it allows for controlled conditions and efficient product generation. Olivine, an abundant and reactive silicate mineral, is used as the feedstock due to its cost-effectiveness and availability, especially in regions with ultramafic rock deposits, like Pakistan[15][16]. The olivine is mined and processed into slurry with water, and then exposed to compressed CO_2 in a reactor, forming $MgCO_3$ and SiO_2. The slurry undergoes a series of separation and purification processes, with CO_2 being recycled and reused to maximize the efficiency of the process [14].s.

Material and Methods:

This section outlines the approach for CO_2 sequestration via mineral carbonation. It covers the following aspects:

1. **Process Overview**: A step-by-step description of how CO_2 is captured and converted into stable carbonates through mineral carbonation.
2. **Raw Materials Required**: Identification of essential raw materials, such as olivine (Mg_2SiO_4), water, and CO_2. Olivine is the primary feedstock due to its high reactivity and abundance, making it an economical choice for carbonation.
3. **Chemical Reactions**: The carbonation reaction, where olivine reacts with CO_2 to form magnesium carbonate ($MgCO_3$) and silica (SiO_2).

The simplified reaction is:

$$2CO_2 + Mg_2SiO_4 \rightarrow 2MgCO_3 + SiO_2 \quad (1)$$

This exothermic reaction helps in CO_2 sequestration, converting it into stable minerals that can be utilized in industrial applications.

4. **Mass and Energy Balance**: Detailed calculations of mass and energy flow within the carbonation plant to ensure efficient process integration. This analysis ensures that the plant operates within the desired parameters, optimizing the conversion and minimizing energy losses.
5. **Key Equipment Design**: The design of essential equipment for the carbonation process, including:

- **Reactor Vessel**: Where the carbonation reaction occurs.
- **Slurry Tank**: For mixing olivine with water to form the slurry.
- **CO_2 Compressor**: To pressurize the CO_2 for efficient reaction.
- **Separation Unit**: For separating the solid magnesium carbonate and silica from the slurry.
- **Coolers and Gas Separators**: To recover CO_2 and ensure its reusability in the system.

Figure 1 below illustrates the process flow chart for the entire CO_2 sequestration process, showing the interconnection between these components and the overall process flow.

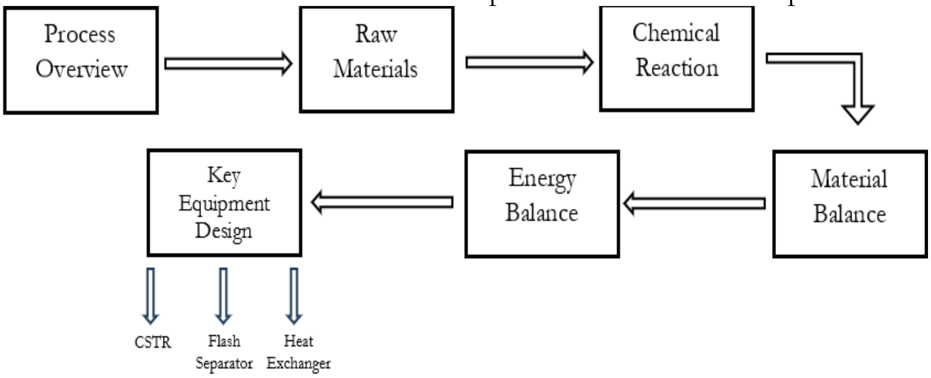

Figure 1. Flow chart of the methodology

Process Overview:

The mineral carbonation process is an addition reaction between a mineral (olivine) and carbon dioxide, resulting in the formation of insoluble carbonates. This process utilizes naturally occurring silicates, and this study focuses specifically on olivine. In the reaction, olivine, also known as Magnesium Orthosilicate, reacts with compressed carbon dioxide to produce stable carbonates. The general carbonation reaction for olivine is given below:

$$2CO_2 + Mg_2SiO_4 \rightarrow 2MgCO_3 + SiO_2 \, (1)$$

This reaction is exothermic and effectively sequesters CO_2 by converting it into solid magnesium carbonate ($MgCO_3$) and silica (SiO_2), which are environmentally stable compounds.

This study focuses on the design of a mineral carbonation plant with a capacity to sequester 30 tons of CO_2 per day. The process is based on ex-situ carbonation, utilizing aqueous olivine as the feedstock. The method involves preparing a slurry of olivine, pre-processing CO_2, reacting the slurry in a continuous stirred tank reactor (CSTR), and separating the final products. A process flow diagram (PFD) has been created to provide a clear understanding of the entire process.

Raw Materials and Chemical Reaction:

The raw materials used in this process are olivine (Mg_2SiO_4), water (used as the medium for slurry preparation), and an additive solution containing 1M sodium chloride (NaCl) and 0.64M sodium bicarbonate ($NaHCO_3$) to control the pH and reaction kinetics. The reactions involved in aqueous mineralization within a continuous stirred tank reactor (CSTR) are outlined below.

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3\text{-}(2)$$

$$Mg_2SiO_4 + 4H+ \rightarrow 2Mg^{+2} + SiO_2 + 2H_2O \ (3)$$

$$Mg^{+2} + HCO_3^{\ -} \rightarrow MgCO^3 + H^+ \ (3)$$

These reactions occur in the reactor within a temperature range of 150°C to 200°C and at pressures between 120 and 150 atm. In the first step, carbon dioxide reacts with water to produce hydrogen ions (H^+) and bicarbonate ions (HCO_3^-). In the second step, the olivine rock reacts with the hydrogen ions to produce magnesium ions (Mg^{2+}), silica (SiO_2), and water. In the third step, magnesium ions react with bicarbonate ions to form solid magnesium carbonate ($MgCO_3$).

Material Balance:

Material balance calculations are performed based on the stoichiometric reactions involved in the olivine carbonation process. To form 1 ton of $MgCO_3$, 1.6 tons of olivine are required for every 1 ton of CO_2 reacted[14]. The process operates at a 50% conversion rate of olivine to reflect realistic conditions and efficiency. The plant is designed to sequester 30 tons of CO_2 per day, equating to 1250 kg/hr of CO_2 sequestration. According to the principle of material balance, input equals output[17].

Figure 2 illustrates the mineral carbonation process of olivine in an aqueous solution, which can also be applied to other natural silicates and industrial residues, such as steel slag [18]. As shown in Figure 2, the olivine undergoes size reduction through crushing and milling to increase the surface area for the catalyzed reaction. The additives are recovered during solid filtration, facilitated by the fine particles of olivine[19].

Energy Balance:

Energy balance calculations are performed to optimize the thermal and mechanical efficiency of the process. To improve the thermal and mechanical aspects of the procedure, energy balances were computed. The energy released is calculated using the energy balance equation:

$$Q=mC\Delta T$$

Where Q is the heat energy, mmm is the mass, C is the specific heat capacity, and ΔT is the temperature change[20].

The heat capacity for slurry tank preparation can be calculated using the following formula:

$$Q=mC\Delta T$$

Where:

- Q is the heat energy required (Joules),

- mmm is the mass of the slurry (kg),
- C is the specific heat capacity of the slurry (J/kg·°C),
- ΔT is the temperature change (°C).

This formula calculates the amount of heat required to raise the temperature of the slurry in the tank by a certain amount.

$$C_{Pmix} = \left(\frac{m_{Mg_2SiO_4}}{m_{mix}}\right) C_{p_{Mg_2SiO_4}} + \left(\frac{m_{H_2O}}{m_{mix}}\right) C_{p_{H_2O}} + \left(\frac{m_{Nacl}}{m_{mix}}\right) C_{p_{NaCl}} + \left(\frac{m_{NaHCO_3}}{m_{mix}}\right) C_{p_{NaHCO_3}}$$

[20]

For energy recovery in the shell-and-tube heat exchanger, the same formula for heat capacity is used, but with adjustments for the different values of mass input and output. The formula remains:

$$Q = mC\Delta T$$

Where:

- Q is the heat energy recovered (Joules),
- mmm is the mass of the fluid (effluent) passing through the heat exchanger (kg),
- C is the specific heat capacity of the effluent (J/kg·°C),
- ΔT is the temperature change (°C) between the inlet and outlet of the heat exchanger.

For the heat exchanger:

- m, changes depending on the flow rate of the effluent,
- C depends on the composition and properties of the effluent fluid,
- ΔT is the difference between the temperature of the effluent when it enters and exits the heat exchanger.

By using this equation, the amount of thermal energy that can be recovered and reused in the process can be calculated. This helps in optimizing the energy efficiency and reducing overall thermal energy consumption.

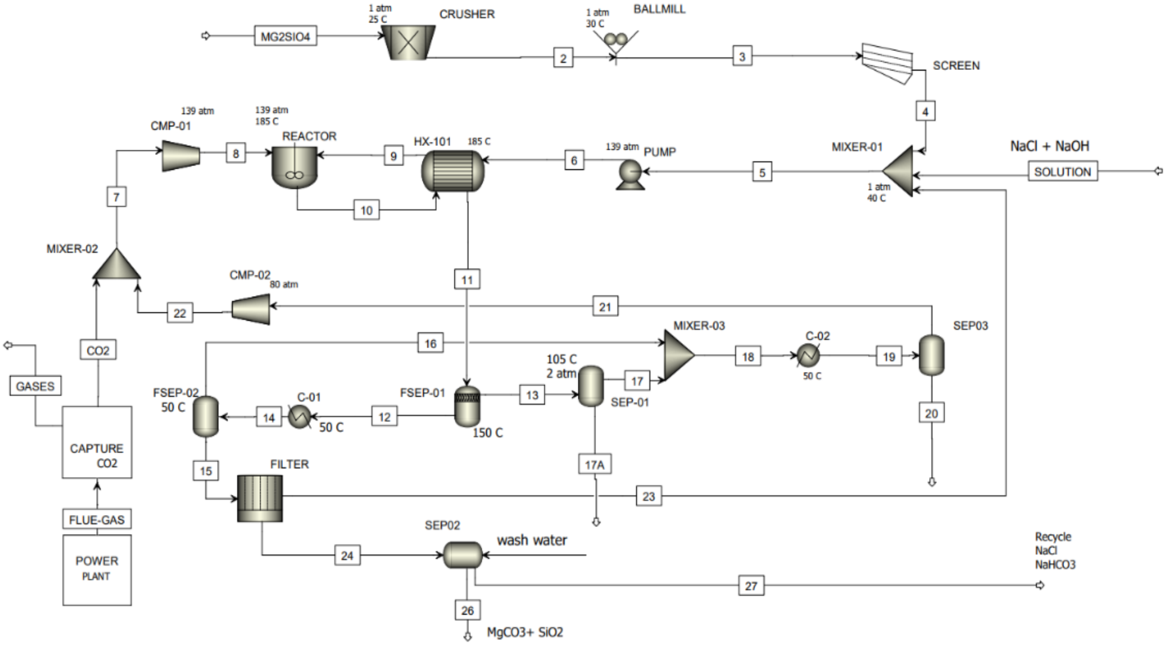

Figure 2. Process flow diagram (PFD) of Mineral carbonation of olivine in aqueous solution created on Aspen Plus.

Key Equipment Designing:

To calculate the power and volume for the major equipment in the mineral carbonation plant, the following formulas are used for the Continuous Stirred Tank Reactor (CSTR), flash separator, and heat exchanger:

1. **Power for CSTR:**

The power required for the CSTR is calculated using the formula:

$$P=KTNr^{3}Da^{5}\ [21]\varrho$$

Where:

- P is the power required (W),
- K is a constant specific to the reactor design,
- T is the temperature of the system (°C),
- Nr is the Reynolds number, a dimensionless number that characterizes the flow regime inside the reactor,
- Da is the characteristic length (diameter or similar) of the reactor (m),
- ϱ is the density of the fluid inside the reactor (kg/m³).

This formula helps calculate the power needed to agitate the slurry and maintain the required reaction conditions inside the CSTR.

2. **Volume for CSTR:**

The volume of the CSTR is calculated using the formula:

$$V = \frac{Fa \times X}{-ra}$$

Where:

- V is the volume of the CSTR (m³),
- Fa is the molar flow rate of the reactant (mol/s),
- X is the conversion rate (dimensionless),
- ra is the rate of reaction (mol/s·m³).

This equation helps determine the required reactor volume based on the molar flow rate, conversion efficiency, and reaction rate [22].

Both formulas are essential for the design and optimization of the CSTR, ensuring that it operates efficiently and at the required power and volume levels for the carbonation process.

Here are the formulas and the explanation for the heat exchanger and flash separator design calculations:

Heat Exchanger Design:

The formula for the design calculation of a heat exchanger is:

$$\frac{1}{Uo} = \frac{1}{hs} + \frac{1}{hod} + Do \times \frac{\ln\left(\frac{Po}{Pin}\right)}{2kw} + \frac{Do}{Din}\left(\frac{1}{hid} + \frac{1}{hi}\right)$$

Where:

- U_o is the overall heat transfer coefficient (W/m²·K),
- h_s is the heat transfer coefficient on the hot side (W/m²·K),
- h_{od} is the heat transfer coefficient on the outer side of the tube (W/m²·K),
- D_o is the outer diameter of the tube (m),
- P_o and P_{in} are the outlet and inlet pressures (Pa),
- kw is the thermal conductivity of the material (W/m·K),
- D_{in} is the inner diameter of the tube (m),
- h_{id} is the heat transfer coefficient inside the tube (W/m²·K),
- h_i is the heat transfer coefficient inside the tube (W/m²·K).

This formula is used to determine the overall heat transfer coefficient, which is a key parameter in designing the heat exchanger to recover and optimize the thermal energy within the system [23].

Flash Separator Design:

1. **Vapor Velocity (Vt):**

The vapor velocity is calculated using the formula:

$$Vt = k\sqrt{\frac{p_l - p_v}{p_v}}$$

Where:

- Vt is the vapor velocity (m/s),
- K is a constant,
- p_l is the density of the liquid phase (kg/m^3),
- p_v is the density of the vapor phase (kg/m^3).

This formula helps calculate the velocity of the vapor in the separator, which is crucial for sizing and designing the flash separator [24].

2. **L/D Ratio:**

The L/D ratio (Length/Diameter ratio) is calculated to determine if using the flash separator for the plant is feasible. If the L/D ratio is too high, it could indicate that the separator is not effective for the required conditions.

3. **Volumetric Flowrate for Liquid and Vapors (Q):**

The volumetric flowrate for liquid and vapor phases is calculated using the formula:

$$Q = \frac{W}{p}$$

Where:

- Q is the volumetric flowrate (m^3/s),
- W is the mass flowrate (kg/s),
- is the density (kg/m^3).

This equation is used to calculate the volumetric flow rates for both liquid and vapor phases, which is essential for sizing the flash separator and ensuring its operation is within the required specifications [25].

These formulas are integral to the design and optimization of the heat exchanger and flash separator, helping to ensure that the processes within the mineral carbonation plant are efficient, effective, and meet operational requirements.

Result and discussion

Table 1. Overall Material Balance

Input		**Output**	
Mg_2SiO_4	**Kg/hr**		**Kg/hr**
Water	2000	$MgCO_3$	1199.9
NaCl	10700.04	SiO_2	428.571
$NaHCO_3$	328.67	Mg_2SiO_4	999.9
CO_2	304.6	CO_2	622.616
	1250	Water	10700.04
		NaCl	328.67
Total		$NaHCO_3$	304.603
Mg_2SiO_4	14583.3	Total	14583.3

Carbon Sequestration Efficiency and Products.

The mineral carbonation plant designed for this study is capable of sequestering 30 tons of CO_2 per day using olivine as the feedstock. The process involves the conversion of CO_2 and magnesium orthosilicate (olivine) into stable magnesium carbonate ($MgCO_3$) as the primary product and silica dioxide (SiO_2) as a by-product. This reaction pathway contributes to CO_2 sequestration while producing valuable industrial products that can be utilized in various industries. The design focuses on efficiency, minimal pre-treatment, and sustainability.

Table 1 presents the overall material balance calculations for each piece of equipment shown in Figure 2. According to the material balance, for every hour of operation, approximately 1199.9 kg of $MgCO_3$ and 428.571 kg of SiO_2 are produced. The majority of the product, $MgCO_3$, has significant industrial applications such as in fertilizers, concrete raw materials, and as a filler in the paint and paper industries.

The 50% conversion rate, accounting for realistic operational limitations, aligns the process with industrial-scale practices and ensures efficiency. The process also achieves material balance, as evidenced by the results in Table 1, confirming the system's reliability for real-world applications.

The recovery of additives via solid filtration highlights the sustainability of the process, minimizing waste generation. Additionally, the use of sieving mechanisms to separate fine silicate and carbonate particles ensures the high purity and quality of the final products, further supporting the feasibility and effectiveness of the mineral carbonation plant design.

Energy Optimization and Thermal Efficiency:

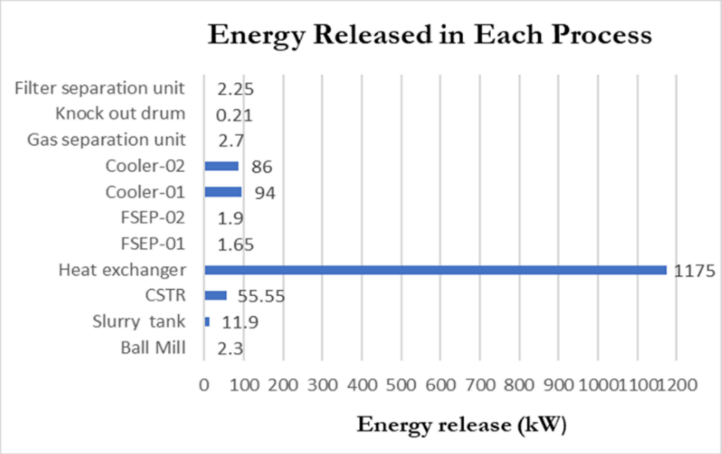

Figure 3. Graphical representation of energy released in each process of the plant

Energy optimization is a crucial aspect of plant design to ensure efficiency and sustainability. In this design:

- The mixing energy for olivine particles in the ball mill is calculated to be **2.3 kW**, which represents the energy required to break down the olivine to an optimal size for reaction.
- The **Continuous Stirred Tank Reactor (CSTR)**, where the carbonation reaction takes place, released **55.55 kW** of thermal energy during the process. This thermal energy is a result of the exothermic nature of the carbonation reaction.
- To recover this thermal energy, a shell-and-tube heat exchanger is incorporated into the design. This heat exchanger facilitates the efficient transfer of heat from the reactor effluent to other parts of the process. It achieved an exchanged heat value of 1175 kW, improving the overall thermal efficiency of the system by recycling the heat and reducing the energy required for heating the incoming fluids.

These energy optimization measures contribute to the overall energy efficiency of the plant, enhancing its sustainability and economic feasibility.

4o mini

The heat exchanger's design, with a heat transfer area of 68.7 m², is pivotal in ensuring effective energy utilization within the mineral carbonation plant. This large surface area enables optimal heat exchange, allowing the system to recover and reuse thermal energy efficiently, thereby significantly reducing operational costs.

Figure 3 illustrates the energy release at each stage of the plant, with the heat exchanger showing a higher thermal energy release compared to other processes. This highlights the critical role of the heat exchanger in recovering and reusing heat from the carbonation reaction, which is vital for minimizing energy consumption.

The calculated thermal efficiencies further demonstrate that the plant is designed to operate under energy-conserving conditions, ensuring reduced energy demand across the system. This approach is particularly valuable in regions like Pakistan, where energy constraints often limit industrial growth and sustainability.

By focusing on energy recovery and minimizing consumption, this plant design not only supports economic feasibility but also aligns with sustainable practices, ensuring that the system can operate efficiently in energy-limited environments.

Process Optimization Through Equipment Design:

The three major equipment specifications are meticulously designed to ensure continuous, efficient operation of the mineral carbonation plant. Each component is optimized for its specific function within the overall system.

1. **CSTR (Continuous Stirred Tank Reactor)**:
   - **Volume**: 1.62 m^3
   - **Power Requirement**: 254.318 kW
   - The CSTR plays a crucial role in the mixing and reaction of CO_2 with aqueous olivine slurry. This large volume ensures the efficient processing of the required CO_2 flow and slurry. The power requirement reflects the energy needed to maintain continuous mixing and facilitate optimal reaction conditions.
2. **Shell-and-Tube Heat Exchanger**:
   - Designed for efficient heat recovery, the shell-and-tube heat exchanger transfers thermal energy from the reaction effluent to the incoming fluid, lowering overall energy consumption and reducing operating costs.
3. **Flash Separator**:
   - The stainless-steel construction ensures durability and resistance to corrosion, effectively separating the liquid and gaseous phases after the reaction. This component is critical for ensuring the purity of the products and maximizing the separation efficiency, which is essential for the high-quality output of magnesium carbonate ($MgCO_3$).

The detailed equipment specification sheets for each major component emphasize the importance of design optimization, ensuring that the plant operates efficiently while minimizing waste and energy consumption.

Table 2. CSTR Equipment specification sheet

Equipment specification sheet	
Type of equipment	Continuous stirred tank reactor (CSTR)
Function	Reacting CO_2 & Mg_2SiO_4 to produce $MgCO_3$
No. of units	1
Conversion	50%
Operating temperature	185°C
Operating pressure	139bar
Design Information	
CSTR Dimensions	Volume = 1.62 m^3
	Diameter = 1.112 m
	Height = 1.668 m
	Depth of liquid = 1.112 m
	Length of impeller = 0.278 m
Power Requirement	254.318 kW
Heat transfer area	39.62 m^2
Material of construction	Carbon steel

Table 2 includes the CSTR equipment sheet specification, showcasing key components and the material selection for each part. Additionally, it highlights the heat transfer area, which is integral to the thermal efficiency of the CSTR design. This ensures the reactor operates effectively, maintaining optimal conditions for the carbonation process.

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Table 3. Shell & Tube Heat Exchanger Equipment specification sheet

Equipment specification sheet	
Type of machine	Type of machine
Function	Function
Operating pressure	Operating pressure
Operating condition	Operating condition
LMTD	LMTD
Design Information	
Heat Transfer Area	Heat Transfer Area
Tube Length	Tube Length
Tube area per pass	Tube area per pass
Shell bundle diameter	Shell bundle diameter
Crossflow area	Crossflow area
Volumetric flowrate	Volumetric flowrate
Overall heat transfer coefficient	Overall heat transfer coefficient
Material of Construction	Material of Construction

Table 3 provides the shell & tube heat exchanger equipment specification sheet, detailing its key components and operational parameters:

- **LMTD (Log Mean Temperature Difference)**: The LMTD value of 11.47°C indicates the effectiveness of heat transfer between two process streams, steam 6 and steam 10 (as depicted in Figure 2). A higher LMTD indicates efficient heat transfer, which enhances the thermal recovery efficiency of the heat exchanger.
- **Heat Transfer Efficiency**: The heat exchanger operates by transferring heat between the two streams. The higher temperature fluid in the tube side improves heat transfer, which contributes to increased thermal efficiency of the overall process. This is crucial for reducing energy consumption, thereby minimizing operational costs.
- **Material of Construction**: Carbon steel is selected for the heat exchanger due to its durability and ability to withstand high temperatures encountered in the process. Its resistance to corrosion and robustness in extreme conditions ensure reliable, long-term operation.
- **Industrial Applicability**: The shell & tube heat exchanger is a widely used design due to its adaptability to a variety of industrial applications. Its high heat transfer rate and efficiency make it a suitable choice for processes that require effective thermal management, such as in the mineral carbonation plant design.

This detailed specification emphasizes the energy-efficient design and cost-effectiveness of the system, ensuring optimized thermal management and sustainable operation.

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Table 4. Flash Separator Equipment specification sheet

Equipment specification sheet	
Type of machine	Type of machine
Function	Function
The mass flowrate of liquid	The mass flowrate of liquid
The mass flowrate of vapors	The mass flowrate of vapors
Vapor Velocity	Vapor Velocity
Volumetric flowrate(liquid)	Volumetric flowrate(liquid)
Volumetric flowrate (vapors)	Volumetric flowrate (vapors)
Vessel diameter	Vessel diameter
Liquid depth	Liquid depth
Height of vapor space	Height of vapor space

Flooding height	Flooding height
Mist extractor clearance	Mist extractor clearance
L/D ratio	L/D ratio
Wall thickness	Wall thickness
Material of construction	Material of construction

Table 4 presents the flash separator equipment specification sheet, outlining key design parameters and operational considerations:

- **L/D Ratio**: The **L/D value** (Length/Diameter ratio) is less than 5.5, indicating that the use of the flash separator is appropriate for the plant's design. A low L/D ratio indicates that the separator is well-suited for efficient phase separation (liquid and vapor) under operating conditions, ensuring effective separation and maximizing efficiency.
- **Separation Efficiency**: The flash separator's ability to efficiently separate the liquid and gaseous phases is demonstrated by the low L/D ratio, which ensures the desired separation of phases with minimal energy loss.
- **Material of Construction**: Stainless steel is chosen for the flash separator due to its compatibility with the materials involved (such as CO_2, water, and olivine slurry), along with its durability. Stainless steel's resistance to corrosion and its ability to withstand the high-pressure conditions typical of separators ensure longevity and reliability in the plant.

This specification confirms the flash separator's effectiveness in maintaining separation efficiency and ensures long-term performance under harsh operating conditions.

Discussion:

The findings of this study highlight the viability and scalability of mineral carbonation using olivine for CO_2 sequestration, offering significant environmental and economic benefits. The key takeaways are:

- **CO_2 Conversion**: The designed process, capable of sequestering 30 tons of CO_2 per day, converts CO_2 into magnesium carbonate ($MgCO_3$) and silica dioxide (SiO_2). Both by-products have notable industrial applications, strengthening the process's commercial viability.
- **Industrial Applications**:
  - **$MgCO_3$**: This compound has multiple uses, including as a fertilizer, concrete raw material, and filler in paints and paper. In particular, its low-carbon properties make it valuable in concrete applications, contributing to CO_2 reduction in the construction industry.
  - **SiO_2**: This by-product is utilized in glass manufacturing and as a precursor for silicon semiconductor production, with applications in fields such as rice hull-derived silicon.
- **Energy Efficiency**: The integration of heat recovery systems within the plant design improves energy efficiency, thereby reducing both costs and environmental impact. The thermal recovery in the process contributes significantly to operational cost reduction.
- **Engineering and Material Selection**: Given the high-pressure (139 bar) and high-temperature (185°C) conditions required for carbonation, carbon steel is selected for the reactor's construction due to its structural durability and corrosion resistance. This material choice is critical for large-scale deployment. However, future research may explore alternative materials or coatings to enhance reactor lifespan and operational efficiency.
- **CO_2 Capture and Transport**: While the study focuses on the carbonation process, it highlights the importance of optimizing the capture and transport of CO_2. Utilizing waste CO_2 from industrial processes (e.g., flue gases) instead of relying on pure CO_2 streams could significantly improve the economics of the process.

In conclusion, this study underscores the dual-purpose nature of mineral carbonation, addressing both CO_2 reduction and the growing demand for sustainable industrial materials. The economic potential of the reaction by-products and the energy efficiency improvements make this technology a promising solution for carbon capture and utilization. Further research and optimization of CO_2 capture and reactor materials will enhance the commercial feasibility and long-term viability of the process.

Sustainability and Economic Impact:

The dependence on olivine, an abundant and cost-effective silicate mineral, underscores the economic and environmental advantages of this mineral carbonation process. Key points include:

- **Local Feedstock Availability**: In Pakistan, the presence of ultramafic rocks, such as peridot, offers a local and cost-effective feedstock source. This reduces the need for imported materials, further enhancing the process's economic feasibility.
- **Product Recovery and Income Generation**: The recovery of $MgCO_3$ (magnesium carbonate) and SiO_2 (silica dioxide) creates opportunities for income generation, contributing to covering operational costs and improving economic sustainability. These by-products have significant industrial applications, including in fertilizer production**,** concrete manufacturing, and paint and paper industries.
- **Reaction Enhancement**: The use of additive solutions, such as sodium chloride (NaCl) and sodium bicarbonate ($NaHCO_3$), improves reaction kinetics, optimizing the carbonation process while keeping it simple and cost-effective. This approach balances operational efficiency with minimal complexity.
- **Climate Change Mitigation**: This process is aligned with global efforts to mitigate climate change, particularly by addressing CO_2 emissions from fossil fuel consumption. By converting CO_2 into stable carbonates, it provides a scalable and economically viable solution to carbon capture and storage (CCS) technologies.
- **Industrial Growth and Sustainable Development**: The plant design supports Pakistan's industrial growth by utilizing local feedstocks and reducing carbon emissions. It offers a pathway for sustainable development by integrating carbon sequestration with industrial applications, reducing the country's carbon footprint while fostering eco-friendly industries.

Overall, the mineral carbonation process offers a sustainable solution for CO_2 sequestration, with economic benefits derived from by-product recovery and local resource use, aligning with Pakistan's goals for industrial growth and climate action.

Process limitations:

Mineral carbonation presents a promising and sustainable solution for CO_2 sequestration, particularly due to its ability to form stable carbonates like magnesium carbonate ($MgCO_3$), which reduces the risk of CO_2 being released back into the atmosphere. However, several process limitations hinder its large-scale implementation:

1. **Passivation Layer Formation**:
   - The presence of silica-rich layers on the surface of olivine minerals creates a passivation layer, which **slows** down the carbonation process. This layer restricts the effective surface area available for the reaction, reducing the efficiency of CO_2 sequestration and requiring more time for the process to complete.
2. **Slow Reaction Kinetics**:
   - The dissolution kinetics of olivine, influenced by weakly acidic conditions, are relatively slow. This leads to slow reaction rates and limits the overall effectiveness of the carbonation process. The formation of the passivation layer also contributes to these slow reaction kinetics, as it obstructs the mineral's ability to react efficiently with CO_2.
3. **High Operational Costs**:
   - **Energy-intensive nature**: The mineral carbonation process requires high temperatures and pressures, increasing the energy demand.

- **Mining and Pre-treatment Costs**: The extraction, grinding, and pre-treatment of silicate minerals, such as olivine, add to the overall cost of the process.
- These high operational costs are one of the major barriers to large-scale commercialization, making it economically challenging to implement the process on a wide scale.

In summary, while mineral carbonation offers a durable solution for CO_2 sequestration, addressing the slow reaction kinetics, passivation layer formation, and high operational costs are essential for improving its economic viability and achieving large-scale commercial deployment.

Conclusion:

The motivation for this study lies in the urgent need to reduce CO_2 emissions and simultaneously produce magnesium carbonate ($MgCO_3$), a valuable product. The conceptual design of this process focuses on developing a cost-effective and environmentally friendly solution. As fossil fuel consumption continues to rise, so do CO_2 emissions, necessitating the need for effective carbon capture and sequestration (CCS) technologies.

Key aspects of the study include:

1. **Ex-situ Mineral Carbonation**: This process captures and stores CO_2 through carbonation, offering a practical method for CO_2 sequestration.
2. **Process Flow Diagram (PFD)**: A PFD has been created to visualize the working of the entire plant, helping to understand the sequence and integration of processes involved in CO_2 capture and $MgCO_3$ production.
3. **Material and Energy Balance**: These balances have been applied to ensure that the plant operates efficiently. The energy balance indicates that although the process is energy-intensive, heat recovery mechanisms are in place, utilizing recycled streams and process streams for heat exchange, thereby optimizing energy use.
4. **Product and By-product Applications**:
   - **Magnesium Carbonate ($MgCO_3$)**: This valuable product can be used in several industrial applications, such as fireproofing, concrete production, dusting powders, toothpaste, and fire extinguishers.
   - **Silica Dioxide (SiO_2)**: The by-product can be used in glass manufacturing, as food additives, and in other industrial processes.
5. **Economic Viability**: Both the main product ($MgCO_3$) and by-product (SiO_2) have high market value, which supports the economic feasibility of the process. They can be easily sold, contributing to cost recovery and enhancing the financial sustainability of the project.
6. **Practical Implications**: The project not only addresses the CO_2 emissions issue but also contributes to sustainability and the development of renewable energy solutions. The study translates theoretical knowledge into practical applications, providing valuable insights into process engineering and plant design.

In conclusion, this project is a significant step towards sustainable development, offering a feasible solution to CO_2 sequestration while also creating valuable industrial products.

Challenges and Future Perspectives: Although the results are encouraging, some challenges need to be overcome to enable large-scale deployment. The passivation layer created through the carbonation reaction is a major challenge, as it lowers reaction efficiency. This work emphasizes the need for a process design that minimizes or eliminates pre-treatment activation. Additional research is also needed for the optimization of reaction kinetics and enhancing additive recovery processes. Lower energy requirements are needed to reduce the high-cost value. The aim of the study is ex-situ carbonation, which provides controlled conditions, giving constant results. Whereas, the in-situ method might offer an alternative for certain applications, especially in areas with applicable geological formations. Investigating hybrid approaches that give the benefits of both methods might discover innovative solutions.

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