

Article

Techno-Economic Analysis of Mineralization and Utilization of CO₂ in Recycled Concrete Aggregates

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Abstract: Considering the dangers and risks posed by climate change, many countries and organizations have pledged to achieve “net-zero emissions” by 2050. The present work introduces a new approach that addresses the growing global carbon emissions issue by integrating CO₂ capture and sequestration through the carbonation of recycled concrete aggregates (RCAs), producing an alternative sand (AS) product. This study explores the capture of low-concentration CO₂ and its suitability for sequestration into RCA. The integration of RCA in the process allows concrete manufacturers to reduce their reliance on mined sand, thereby minimizing its impact on the environment. A techno-economic analysis (TEA) was conducted on the CO₂ absorption and mineralization process to assess its economic viability across various processing scales, from 150 kt CO₂ per year to 1 Mt CO₂ per year. Initial bench-scale experiments show that RCA samples have a carbonation capacity of 10% by mass—these experimental results were used to conduct a TEA using Aspen Plus and an Aspen Process Economic Analyzer (APEA). The TEA results reveal a cost of 11.02 USD/t AS at the smallest scale and 8.02 USD/t AS at the largest scale.

Keywords: techno-economic analysis; ex situ mineralization; carbon capture; recycled concrete aggregates; low-concentration CO₂



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1. Introduction

The world is currently facing severe climate change challenges driven by increasing levels of carbon dioxide (CO₂) and other greenhouse gas (GHG) emissions. Fossil fuel burning in industries like energy, transportation, and heavy industries is the main source of CO₂ emissions, which account for more than 75% of all GHG emissions. The Paris Agreement’s objectives, which include keeping the increase in global temperature to 1.5–2 °C over pre-industrial levels, are in line with the urgency of reducing CO₂ emissions [1]. Even though CO₂ emissions have decreased recently, concentration levels are still unsustainable, necessitating creative solutions to reach net-zero emissions by 2050 [2].

Power generation is a leading source of global CO₂ emissions, with fossil-fuel-based plants driving much of this impact. Despite being a greener alternative to coal, natural gas combined cycle (NGCC) facilities nevertheless emit a significant quantity of CO₂. Carbon capture, utilization, and storage (CCUS) has become one of the most successful solutions to reduce CO₂ emissions from industrial and electricity sources. The process involves separating CO₂ from flue gases and storing it over an extended period. A significant portion of global CO₂ emissions between 2019 and 2022 came from the electricity sector, underscoring the necessity of additional technical advancement to reduce emissions from this vital industry [3]. Given that the use of natural gas for power generation has been

rising since 1990 and has since overtaken coal as the most utilized source for electricity production, there is a need to investigate the suitability of CO₂ capture for natural gas power plants [4]. Natural gas plants emit a flue gas that is generally low in concentration (3–4 vol%), thus having a larger volume of gas to treat compared to coal-fired power plants, which generate higher concentrations of CO₂ in their flue gas [5].

Among the various CO₂ capture technologies, including post-combustion, pre-combustion, and oxy-combustion, post-combustion capture using chemical solvents is the most suitable method for NGCC plants [6–8]. Conventional solvents like monoethanolamine (MEA) are widely used for CO₂ capture but have limitations due to high regeneration costs and degradation issues [9,10]. Aqueous ammonia, however, offers a promising alternative, achieving high CO₂ removal efficiency with significantly lower energy requirements. This advantage is particularly valuable in NGCC applications, where the relatively low CO₂ concentration in flue gas demands efficient capture solutions [11]. Using aqueous ammonia for CO₂ capture presents a benefit by producing a CO₂-rich ammonium carbonate solution, which can be directly used in subsequent mineralization reactions. This solution, containing concentrated CO₂, can react with alkaline solid wastes like recycled concrete aggregate (RCA), incinerator bottom ash (IBA), and steel slag, facilitating the formation of stable carbonates. This integrated approach enhances CO₂ sequestration while addressing industrial waste management by converting solid waste into carbonates that lock CO₂ permanently [12].

Carbon capture and utilization by mineralization (CCUM) represents a promising approach to permanently sequester CO₂ through reactions with calcium- and magnesium-rich materials, converting CO₂ into stable carbonates that can lock the gas in solid form [13]. Traditional CCUS often involves subsurface injection into geological formations. Lackner et al. first proposed the idea of reacting CO₂ with minerals that contain calcium or magnesium [14]. These minerals, however, require significant heat input to activate them for mineralization reactions, which lead to secondary emissions. Ex situ CO₂ mineralization by using industrial by-products such as RCA and steel slag allows for both efficient CO₂ sequestration and the beneficial reuse of industrial by-products. In addition, this option is the only CO₂ sequestration method available where large underground reservoirs do not exist, and storing CO₂ in the ocean is not feasible [15,16]. It is particularly valuable for land-scarce regions like Singapore, where efficient waste management is critical. By incorporating alkaline solid waste, CCUM supports emission reduction and sustainable waste management goals, aligning with circular economy principles to minimize landfill use and conserve natural resources.

RCA is mainly composed of concrete obtained from construction and demolition waste. Typically, this waste is crushed and filtered to remove foreign objects and metals, followed by a screening process to sort the aggregates into respective sizes [17]. Studies have shown that RCA can replace natural aggregates in concrete manufacturing, showing comparable structural properties that are within acceptable and safe limits of structural members [18]. The use of RCA can potentially reduce manufacturers' reliance on natural aggregates, such as sand and gravel, hence reducing the need to mine these materials. Sand is a natural resource that is heavily exploited and can lead to many environmental impacts, such as the erosion of coasts, which can lead to less protection against extreme weather such as floods [19]. Additionally, RCA provides an effective medium for mineral carbonation, with CaO reacting readily with CO₂ to form stable calcium carbonate (CaCO₃). By converting CO₂ into a solid carbonate form, RCA serves as both a carbon sink and a sustainable construction material, addressing two critical environmental concerns: reducing construction waste and mitigating CO₂ emissions.

In this study, the proposed integration of ammonia-based CO₂ capture with RCA mineralization presents a holistic solution to NGCC CO₂ emissions. This process is particularly advantageous in NGCC contexts, where the CO₂ concentration is lower and traditional solvents become less efficient. After initial capture, the carbonated ammonium solution reacts with RCA, where the CaO component reacts with ammonium carbonate to produce CaCO₃. This dual-phase approach optimizes energy use, minimizes the need for additional processing, and produces a carbonated aggregate with potential applications in construction.

2. Methods

A process flow diagram (PFD) of the absorption and mineralization process is shown in Figure 1. The process described in this study aims to capture CO₂ in different scales from 150 kt CO₂ per year to 1 Mt CO₂ per year of CO₂ annually from an NGCC power plant. Aspen Plus[®] V14 software was utilized to model the process and perform techno-economic analysis (TEA) [20]. It was selected for modeling in this study due to its proven effectiveness in similar techno-economic analyses of carbon capture processes in NGCC and PC power plants [21].

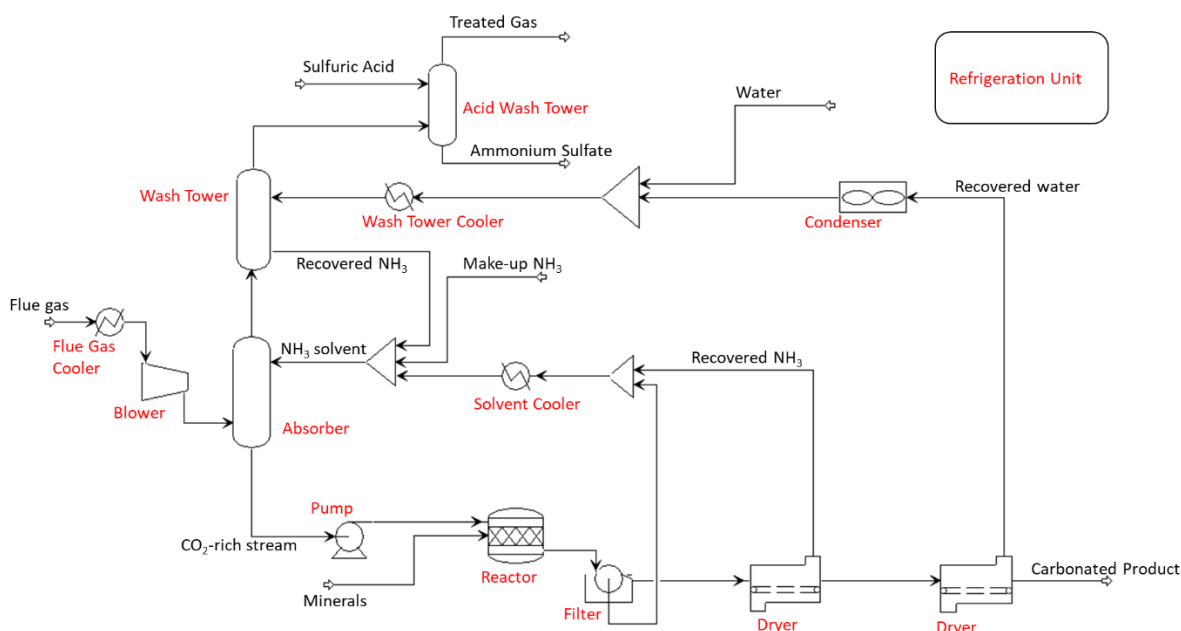


Figure 1. Process flow diagram (PFD) of absorption and mineralization process.

The pilot-scale CO₂ capture process, which operates for 8000 h each year, consists of two main sections: the CO₂ absorption section and the mineralization section for solvent recovery. A packed absorber column is employed for CO₂ absorption, allowing flue gas to flow through and interact with an aqueous ammonia solution in a counter-current fashion. This interaction results in the formation of a carbonated ammonium solution, which comprises various ionic species and complexes, including ammonium carbonate, bicarbonate, and carbamate. The aqueous ammonia tank and the jacket of the absorption column are maintained at a temperature of 20 °C. Chemical interactions within the absorber are modeled using the Electrolyte Non-Random Two Liquid (ELECNRTL) framework within Aspen Plus[®] V14 [22,23]. This model is robust enough to be adapted for a full-scale CO₂ capture plant, facilitating further evaluations of the system, exploring solvent potential, and identifying possible energy savings. Rate-based modeling techniques are employed due to their ability to accurately capture the kinetics of reactions and mass transfer processes, enabling a more comprehensive understanding of the dynamic interactions within the

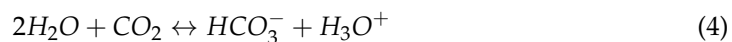
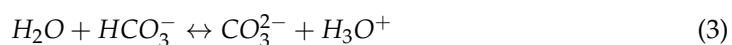
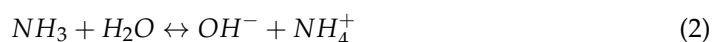
absorption system. These models also offer flexibility for optimizing operational parameters and enhancing the overall efficiency of CO₂ capture processes.

In the mineralization section, the carbonated RCA undergoes filtration and is subjected to two-stage drying to recover the ammonia solvent for reuse in the absorber and wash tower. More volatile ammonia is recovered during the initial drying stage and returned to the absorber, while water is collected in the second drying stage for use in the wash tower.

Controlling ammonia emissions from the system is crucial for environmental compliance and minimizing the impact on air quality. To facilitate effective ammonia recovery, a water wash tower is used to capture ammonia gas released from the upper section of the absorber. Furthermore, an acid wash tower is incorporated to treat ammonia concentrations that may reach up to 2000 ppm, ensuring that emissions are reduced to comply with local regulations of 43.07 ppm (30 mg/Nm³) [24]. This dual approach not only enhances ammonia recovery but also mitigates the potential environmental risks associated with excessive ammonia emissions. In this study, the flue gas primarily from an NGCC power plant is assumed to contain 3% CO₂, which is consistent with the typical content of CO₂ at concentrations of 3–4%. The wash towers and reactor function at 25 °C under the same pressure conditions.

2.1. Absorption Section

This work explores the capture of CO₂ from a low-concentration source using an absorber unit. Flue gas containing CO₂ is contacted in a counter-current fashion with an ammonia solvent. Table 1 provides detailed information on the composition and conditions of the flue gas within the absorber. As ammonia is a relatively volatile component, a relatively lean solution was selected as the solvent. This design aims to minimize ammonia slippage from the upper section of the absorber tower, thereby reducing freshwater utilization in the subsequent recovery of ammonia via a wash tower. The electrolyte non-random two-liquid (ELECNRTL) thermodynamic method was used to model the reactions within the absorption and water wash section of the process. Que and Chen's work in 2011 [25] details the behavior of the NH₃-CO₂-H₂O system for the ELECNRTL model. The equations are shown as (1)~(5). In this work, the Redlich–Kwong equation of state (EOS) is used to model interactions in the vapor phase.



The process was modeled using Aspen Plus V14, which assumes that the flue gas from NGCC power plants contains 3–4% CO₂, a typical concentration for such facilities. The simulation also assumes a steady-state operation at 20 °C for the CO₂ absorption section using aqueous ammonia as the solvent. This choice of solvent is based on its proven efficiency in capturing low concentrations of CO₂ while minimizing regeneration costs and solvent losses. The system can maintain environmental compliance by efficiently recovering and recycling ammonia emissions through integrated wash towers.

Table 1. Flue gas composition and absorber conditions.

Parameter	Unit	Value
Flue Gas Composition		
CO ₂	vol%	3
O ₂	vol%	21
N ₂	vol%	76
Flue Gas Conditions		
Temperature	°C	250
Pressure	bar	1
Absorber Conditions		
Temperature	°C	20–50
Pressure	bar	1
Operation		
Operation time	hours/year	8000
Solvent		
NH ₃ concentration	wt%	1.3
Solvent-to-CO ₂ ratio	molNH ₃ /molCO ₂	2
Emissions		
NH ₃ limit	ppmv	41 [10]

2.2. Mineralization Section

When carbon dioxide (CO₂) interacts with the metal oxides (MO) present in RCA, it undergoes a reaction to produce the corresponding carbonate. The process follows the chemical equation $(M)O + CO_2 = (M)CO_3$, where M is calcium (Ca) and magnesium (Mg) in the studied system. The mineralization section consists of a continuous stirred tank reactor (CSTR) followed by a series of a filter, dryers, and condensers to dry the alternative sand products and recover ammonia solvent from the slurry. Studies have shown that the mineralization of RCA has a CO₂ uptake of 10% to 19.8% [26], and an investigation of the ratio of ammonium carbonate to CaO in the RCA was conducted to optimize the conversion [27]. In this study, bench-scale experiments were conducted as a foundational step to validate the proposed methodology. The experiments examined the concentration of ammonium carbonate in the absorption liquid product and its ratio to calcium oxide in the RCA. The results indicate a CO₂ capacity of approximately 10% by mass when using an absorption liquid product containing 5 wt% ammonium carbonate and a ratio of 0.25. Detailed experimental parameters and resultant carbonation outcomes are provided in the Supplementary Information. It is important to note that, for the purposes of this study, a CO₂ uptake of 10% by mass was assumed. Consequently, the quantity of mineral material introduced into the CSTR was calculated to be tenfold the amount of CO₂ introduced.

The ammonia solvent was recovered in two parts—the first dryer was designed for a lower heat duty to recover most of the ammonia, while the second dryer was designed at a slightly higher heat duty to recover the remaining water. The resulting solid contained approximately 10% liquid by mass. Heat energy released from the hot flue gas in the flue gas cooler was recovered in the dryers.

2.3. Techno-Economic Analysis

2.3.1. CapEx (Capital Expenditure)

The process, as illustrated in Figure 1, was simulated using Aspen Plus V14, and the economic evaluation was conducted using Aspen Process Economic Analyzer (APEA). All cost values presented are in 2022 United States dollars (USD). For the CapEx calculation, a depreciation period of 20 years is assumed. The scaling analysis for the techno-economic assessment (TEA) was initially based on a capacity of 150 kilotonnes (kt) of CO₂ per year. Subsequent TEAs were performed on larger scales of 200 kt, 300 kt, and 1 million tonnes (Mt) of CO₂ per year, with the main scale-up considerations being the size of the equipment and the increased energy requirements for solvent recovery.

2.3.2. OpEx (Operational Expenditure)

Operational expenditure (OpEx) optimization was considered through heat recovery from the flue gas to reduce the external heat input required for solvent recovery. In the case study from the National Energy Technology Laboratory (NETL), the carbon capture, utilization, and storage (CCUS) unit derive heat input from the heat recovery steam generation (HRSG) unit in the power plant. For simplicity, the TEA explores the use of natural gas-fired heat, with a CO₂ emission factor of 50.2 kg CO₂/GJ and a cost of USD 9.76 per GJ [28,29]. Additionally, an average electricity price of 0.16 USD/kWh and an emission factor of 0.475 kg CO₂/kWh were used [30,31]. Cooling duties, calculated in Aspen Plus, were transferred to APEA, where a centrifugal refrigerant unit was sized accordingly. Emissions associated with electricity consumption were accounted for in the TEA.

3. Results

3.1. Cost Analysis

A cost analysis reveals a decreasing trend in the cost of the production of the alternative sand with an increasing scale, demonstrating economies of scale in this process. The cost of production of AS ranges from USD 11.02 to USD 8.02 per tonne from the smallest to the largest scale, respectively. A detailed comparison of the cost results can be found in Table 2 and are visualized in Figure 2.

Table 2. Cost analysis summary.

Description	Unit	Value				
Scale	t CO ₂ /year	150 kt	200 kt	300 kt	1 Mt	
TCI	USD					
CapEx	USD/t AS	1.86	1.71	1.55	1.54	
OpEx	USD/t AS	9.16	7.77	6.93	6.48	
Total Production Cost	USD/t AS	11.02	9.47	8.49	8.02	
Energy Consumption	Unit	Value				
Heating	GJ/t AS	0.31	0.23	0.19	0.13	
Electricity	GJ/t AS	0.06	0.06	0.05	0.05	
Total	GJ/t AS	0.37	0.29	0.24	0.18	

Across all four cases analyzed, there is a noticeable decrease in both energy consumption and capture cost as production scale increases. While this phenomenon can largely be attributed to economies of scale, it is important to note that the primary driver behind this trend is the utilization of heat recovered from hot flue gas. As the production scale

increases, the reliance on external heat input in the dryer systems diminishes, resulting in reduced operating costs and energy consumption, as illustrated in Figure 2.

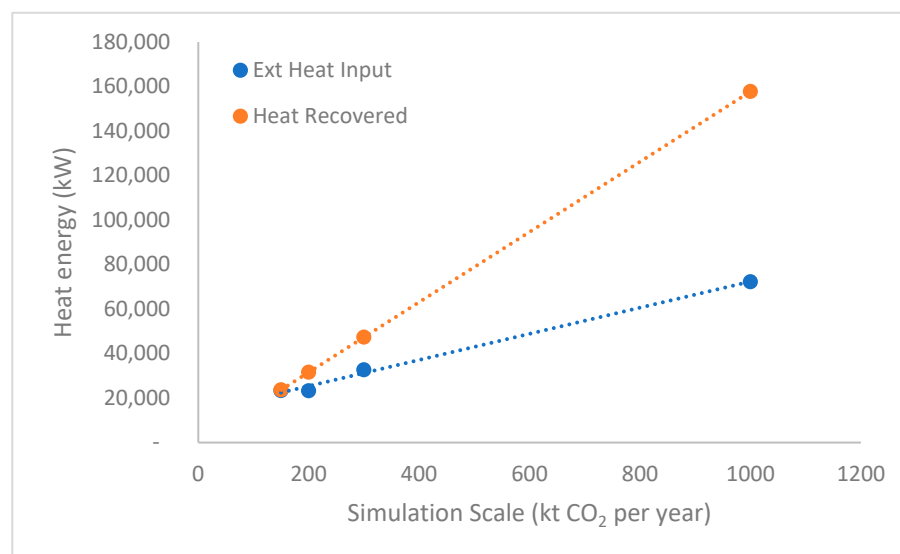


Figure 2. Heat energy composition (external heat input in blue; recovered heat in orange).

The economies of scale trend apply to CapEx as well. However, this trend appears to plateau towards larger scales. Despite a large increase in scale from 300 kt to 1 Mt CO₂ per year, the change in CapEx is only 1% compared to a 8.4% change from 150 kt to 200 kt CO₂ per year. Conversely, the change in OpEx from 300 kt to 1 Mt CO₂ per year is 6.6% compared to a 15.2% change from 150 kt to 200 kt CO₂ per year. This suggests that while CapEx has reached a stable level, the OpEx per tonne of AS still has room for optimization. Considering that in Singapore, power generation alone generated 21 Mt of CO₂ in 2021 [32], there is room for OpEx to be reduced to a more affordable and energy-efficient level.

A significant proportion of the costs can be attributed to cooling and separation equipment, such as the absorber, wash tower, flue gas cooler, and filter, accounting for up to 40% of the TCI. Details of the direct costs of the individual equipment and energy consumption of the relevant equipment can be found in the Supplementary Information (SI).

3.2. CO₂ Abatement

During the mineralization reaction, CO₂ is sequestered permanently in the RCA as carbonates. The method of calculating CO₂ abatement is designed to assess the CO₂ abatement associated with producing the carbonated RCA, providing a specific metric for the product's carbon footprint. The TEA results show that as the scale increases, CO₂ abatement shows little variation. The method of calculating CO₂ abatement can be found in the following equation, and the results are shown in Table 3:

$$CO_2 \text{ abatement} = CO_2 \text{ captured via carbonation} - CO_2 \text{ emissions (heat + electricity)} \quad (6)$$

Table 3. CO₂ abatement result.

Scale	kt CO ₂ /Year	150	200	300	1000
CO ₂ Abated	kg CO ₂ /year	1.52×10^8	1.61×10^8	2.41×10^8	8.02×10^8

The data in Table 2 indicate that scaling up the CO₂ mineralization process in RCA leads to a significant reduction in energy consumption per ton of aggregate. This improvement is primarily due to enhanced thermal efficiency and economies of scale, which

allow for a more effective implementation of heat recovery systems. Despite this substantial decrease in energy consumption, the total CO₂ abated increases proportionally with scale, from approximately 151.7 million kg/year at 150 kt to 801.8 million kg/year at 1 Mt. This proportional increase suggests that the CO₂ capture efficiency of the process remains consistent across different scales.

The relatively small impact of energy-related CO₂ emissions on the overall CO₂ balance further underscores the effectiveness of the CO₂ sequestration process in RCA. Although energy consumption per ton decreases with scale, the CO₂ emissions associated with this energy are minimal compared to the total CO₂ captured in the RCA. This indicates that the net CO₂ abatement is largely dominated by the sequestration capacity of the RCA, with energy-related emissions having a negligible effect. Therefore, while scaling up enhances energy efficiency, consistent CO₂ capture efficiency across scales ensures that the process remains effective in sequestering CO₂ regardless of the production volume. To further optimize the process, attention should be given to enhancing the CO₂ sequestration capacity of RCA and utilizing low-carbon energy sources to minimize any residual emissions.

4. Discussion

4.1. Energy Consumption

Heating energy consumption decreases from 0.31 GJ/t AS at 150 kt CO₂/year to 0.13 GJ/t AS at 1 Mt CO₂/year, marking a 58% reduction and indicating significant thermal efficiency gains with scale. Electricity consumption shows minimal variation, dropping slightly from 0.06 GJ/t AS to 0.05 GJ/t AS over the same range. The overall energy consumption therefore falls from 0.37 GJ/t AS at 150 kt to 0.18 GJ/t AS at 1 Mt, a total reduction of 51% (details on the mass and energy balance of the process are shown in Supplementary Material S2). Table S9 provides a detailed breakdown of energy consumption and heat recovery across various scales of CO₂ capture, ranging from 150 kt to 1000 kt CO₂ per year. As the scale increases, the total heat requirement rises from 47,000 kW at the smallest scale to 230,000 kW at the largest. Correspondingly, the heat requirement per tonne of CO₂ captured decreases from 0.31 kW/t CO₂ to 0.23 kW/t CO₂, demonstrating improved efficiency at larger scales. The amount of heat recovered also increases significantly with scale, from 23,666 kW to 157,776 kW, accounting for a larger percentage of the total heat requirement—up to 68.6% at the highest scale. This substantial heat recovery reduces the external heat input required, leading to lower operational costs and improved energy efficiency. Additionally, electricity consumption rises with scale, reflecting the increased energy demand for larger operations.

These trends highlight the impact of scaling on reducing energy requirements, particularly through improved thermal efficiency facilitated by economies of scale and the implementation of heat recovery systems. By capturing and reusing waste heat, these systems reduce the need for external heating, thereby enhancing energy efficiency and sustainability.

The importance of heat integration and recovery in optimizing energy efficiency is underscored by these findings. Effective heat recovery not only improves process economics but also supports broader sustainability goals. This approach is well illustrated by the National Energy Technology Laboratory's (NETL) CO₂ capture process using a NGCC power plant, where heat integration from the heat recovery steam generation (HRSG) unit is a key feature. Adopting similar strategies in future implementations of CO₂ mineralization processes can yield comparable benefits, and such strategies will be explored in subsequent studies [33].

4.2. Comparison with Other Methods of CCUS

CCUS encompasses a range of technologies, each with its own advantages and limitations. In comparison to other CCUS methods, our approach using RCA for CO₂ mineralization offers significant benefits in terms of cost, process simplicity, and environmental impact.

4.2.1. Thermal Activation of Natural Minerals

Traditional mineralization processes, such as those involving serpentine, require thermal activation to enhance reactivity, significantly increasing both operational (OpEx) and capital expenditures (CapEx) [34–37]. This thermal activation necessitates additional unit operations, raising the overall cost of CO₂ capture. In contrast, our method utilizes RCA, which does not require such intensive preparation, thereby reducing both the complexity and cost of the process.

4.2.2. Comparison with Sodium Hydroxide Method

Lee et al. assessed the use of sodium hydroxide as a solvent for CO₂ capture, producing sodium bicarbonate at a cost of approximately USD 195 per tonne, showing that the RCA-based process is more economically viable, as our method achieves CO₂ mineralization at a fraction of this cost, ranging from USD 8.02 to USD 11.02 per tonne of alternative sand (AS) produced [38]. Additionally, concrete made from carbonated RCA has demonstrated superior structural properties compared to traditional aggregates, offering an added advantage in construction applications [39].

4.2.3. Resource Benefits

The use of RCA as a feedstock reduces the volume of construction and demolition waste (CDW) sent to landfills and diminishes the concrete industry's reliance on natural aggregates. This reduction in demand for mined sand alleviates environmental issues such as land erosion and the disruption of aquatic ecosystems [19]. The integration of our process not only mitigates waste but also contributes to a circular economy by repurposing industrial by-products into valuable construction materials.

4.2.4. Geological Sequestration

In comparison with other methods of CO₂ sequestration, such as geological sequestration, the process in this work is much simpler and requires far less infrastructure and equipment. Jang et al. found that geological sequestration incurs a high CO₂ transportation cost with a need for excavation operations at sites that are chosen based on a strict qualification process [40]. Bonalumi et al. estimated the cost of CO₂ avoided to be 66.50 USD/t CO₂ by absorption, desorption, and subsequent compression [21], which has applications in geological sequestration and enhanced oil recovery (EOR) processes.

In this study, the RCA mineralization process provides a cost-effective, environmentally friendly, and practical alternative to traditional CCUS methods. It supports sustainable construction practices, reduces waste, and offers a scalable solution for CO₂ capture, especially in urban areas with abundant construction waste.

4.3. Challenges of Ex Situ Mineralization Methods

Ex situ mineralization processes face several significant challenges that hinder their progression to higher technological readiness levels (TRLs) [41]. One of the primary challenges is the high cost of CO₂ capture, which stems from the energy-intensive nature of the process and the need for large quantities of reactants. Slow reaction rates also pose a critical barrier, limiting the overall efficiency and feasibility of scaling up these processes for industrial applications. The preparation of natural minerals for carbonation involves multiple steps, including crushing, grinding, and heat treatment, which contribute

substantially to the overall capture costs. A study by NETL found that massive amounts of natural minerals were required to capture the CO₂ emissions from a 1.3 GW coal-fired power plant, underscoring the logistical and economic challenges associated with sourcing and processing these materials [42]. The requirement for these preparatory steps not only adds to operational costs but also raises concerns about the carbon footprint of the mineralization process itself, potentially offsetting some of the CO₂ sequestration benefits.

In 2018, the United States produced 600 million tons of construction and demolition (C&D) waste, of which 143 million tons were sent to landfill [43]. Assuming a 10% carbonation capacity by mass, ideally, this amount of C&D waste captures 14.3 million tons of CO₂ in a year, which is far more than the CO₂ emissions stated in the NETL study. The mineralization of incinerator fly ash (IFA) from waste-to-energy plants is also a viable option of ex situ methods of mineralization, as demonstrated by Bui Viet et al. [44].

While RCA presents an advantage due to its availability and minimal pre-treatment requirements, other challenges remain. Variability in the composition and the quality of RCA can affect the consistency and efficiency of the mineralization process. Ensuring a steady supply of RCA with predictable properties is crucial for industrial-scale operations. Additionally, the management of by-products and the potential for secondary environmental impacts, such as dust generation and water use, need careful consideration to avoid creating new environmental issues. In conclusion, while RCA-based mineralization offers a promising avenue for CO₂ sequestration, addressing the aforementioned challenges is essential for advancing technology. Continued research and development, combined with strategic investments in infrastructure and regulatory support, will be necessary to overcome these barriers and fully harness the potential of ex situ mineralization in mitigating climate change.

5. Conclusions

In this study, recycled concrete aggregates show potential as CO₂ mineralization media, owing to their simplicity and the availability of raw materials for the process. This process shows potential for implementation in both developed and developing nations, particularly in regions where natural minerals are scarce. The low cost of production for the carbonated RCA (USD 11.02–8.02 depending on scale) provides an alternative to natural aggregates for construction use, since studies have shown that the carbonated RCA has similar, if not superior, properties to concrete produced from natural aggregates. Further studies need to be conducted to optimize energy consumption and enhance reaction rates, thus advancing the technology to higher TRLs. This promising avenue represents a critical step forward in the global effort to mitigate carbon emissions and combat climate change, offering tangible solutions for a sustainable future.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/pr13020410/s1>, Table S1: RCA carbonation results at different reaction conditions; Table S2: Composition of the flue gas utilized in the simulation model; Table S3: Composition mass of the recycled concrete aggregates (RCA) utilized in the simulation model; Table S4: Input-output data for the Absorption Section, with a scale of 200 kilotonnes of CO₂ input; Table S5: Input-output data for the Absorption Section, with a scale of 1000 kilotonnes of CO₂ input; Table S6: Input-output data for the Solvent Recovery/Drying Section, with a scale of 200 kilotonnes of CO₂ input; Table S7: Input-output data for the Solvent Recovery/Drying Section, with a scale of 1000 kilotonnes of CO₂ input; Table S8: TCI Breakdown; Table S9: Energy consumption breakdown.

Author Contributions: W.G.: Process design, Aspen simulation, data analysis, writing—initial draft, visualization, review, and editing. S.Y.: Proof of concept and reaction engineering. R.O.Y.: Proof of concept and reaction engineering. K.H.T.: Proof of concept and reaction engineering. C.W.: Supervision and project administration. L.T.: Proof of concept and reaction engineering, super-

vision, and project administration. S.C.: Process design, Aspen simulation, data analysis, and writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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