Report

Exploring and Evaluating Carbon Capture Technologies for Sequestering Process Carbon Emissions

Angel Badewole, PhD

Sustainability Catalyst Internship || ***Algoma Steel***, University of Toronto

September 2025

Table of Contents

Background

Steel is a vital material in the global economy, as it serves as a critical input across multiple sectors, including construction, automotive, and manufacturing sectors. Global crude steel production exceeded 1.8 billion tonnes in 2024 (World Steel Association, 2025), and is projected to grow by an additional 7% over the next three years (OECD, 2025), underscoring the scale and ubiquity of steel. In Canada, annual production of crude steel was approximately 12.3 million tonnes in 2024, with a market size of US$ 7.8 billion expected by 2030 (Grand View Research, 2025).

As the steel sector expands, there is an increasing need to mitigate its greenhouse gas (GHG) emissions and its environmental impacts. The steel industry is one of the most carbon-intensive industrial sectors, accounting for approximately 7 – 9% of total global GHG emissions (Kim et al., 2022). In Canada, the iron and steel sector ranked as the 4th largest emitter in the industrial sub-sector in 2022, contributing roughly 15 Mt CO_2-eq annually (Khan et al., 2023; Natural Resources Canada, 2024).

Meeting both global and Canadian climate targets will require deep reductions in industrial emissions. As such, the steel sector must scale low-carbon production pathways that can reduce emissions while maintaining output. Therefore, decarbonizing steel is both an environmental imperative and a key component of ensuring the long-term competitiveness of the industry.

To address this challenge, several pathways are being explored to decarbonize the steel sector. These include the use of scrap-based electric arc furnace (EAF), hydrogen-based direct reduced iron (H_2-DRI), improving energy efficiency, and capturing and storing CO_2 from process flue gases (CCUS) (OECD, 2025). Each technology offers varying levels of decarbonization potential. For example, efficiency improvements can only provide marginal reduction in emissions, while H_2-DRI and CCUS technologies have been identified as capable of achieving near net-zero steelmaking.

In addition to these decarbonization strategies, **steel slag carbonation** has recently gained traction due to its potential to support long-term CO_2 sequestration. Steel slag is a byproduct that is formed as a result of the reaction of impurities with injected oxygen in the steelmaking process. It is rich in calcium (Ca) and magnesium (Mg) oxides, which can react with CO_2 to form stable carbonate compounds. When paired with CO_2 removed directly from the atmosphere, e.g., via direct air capture, the process has the potential to deliver negative emissions. Luo and He (2021) estimated 209 Mt of CO_2 can be sequestered from carbonation of global steel slag production (Luo & He, 2021). This is between 9 – 10.5% of the emissions from the iron and steel industry.

As one of the leading flat steel producers in North America, **Algoma Steel** has made major strides towards sustainable steelmaking, as highlighted in its 2024 annual sustainability report (Algoma Steel, 2025). Algoma Steel is positioning itself as a leader environmental stewardship and is as such transitioning to electric arc furnace (EAF) steelmaking, which is expected to reduce up to 70% of its annual carbon emissions, culminating in carbon neutrality by 2050, while simultaneously increasing production capacity by 700kt. Steel slag carbonation holds promise for enhancing Algoma Steel's decarbonization goals. When paired with the planned EAF transition, this could enable Algoma to reach net-negative emissions in the long term.

This report explores the technical potential for steel slag-based carbon capture and sequestration. The mechanisms of carbonation, its process kinetics and its feasibility for industrial scaling are examined using a review of existing literature. A technical assessment follows, supported by data-driven recommendations for implementing steel slag carbonation in industry.

Steel slag carbonation

Steel slag carbonation refers to the reaction of calcium oxide (CaO)-rich and magnesium oxide (MgO)-rich slag with CO_2 to form stable carbonate compounds. While this reaction occurs naturally, it proceeds at a very slow rate. Thus, it needs to be accelerated through optimized process conditions. The carbonation of steel slag is considered an example of mineral carbonation, and its potential for CO_2 sequestration depends on factors such as slag composition, particle size and other reaction conditions as discussed in a later section of the report (Wang, Wang, et al., 2024).

Mechanism of steel-slag carbonation

The fundamental reactions involved in steel slag carbonation are below (DiGiovanni et al., 2024):

$$CaO_{(s)} + CO_{2(g)} \rightarrow CaCO_{3(s)}$$

$$MgO + CO_2 \rightarrow MgCO_{3(s)}$$

These reactions transform reactive oxides in the slag into stable, solid carbonates, therefore storing CO_2 in a permanent mineral form. Methods of steel slag carbonation are classified into two broad categories: (1) Direct carbonation and (2) Indirect carbonation.

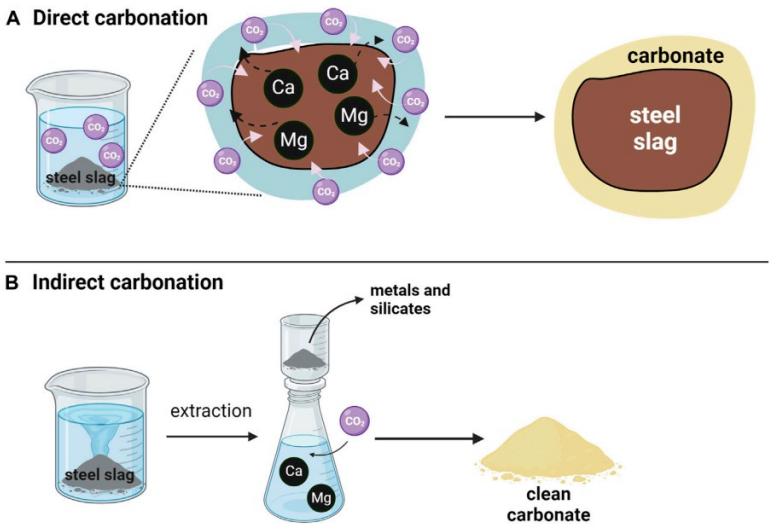


Figure 1. Schematic of steel slag carbonation process. Panel A: Direct aqueous carbonation; Panel B: Indirect carbonation. [Adapted from (Biava et al., 2024)].

Direct carbonation

Direct carbonation involves the direct reaction of steel slag with CO_2. This can occur under either dry or wet conditions, referred to as dry (gas-solid) carbonation and wet (aqueous) carbonation respectively.

Direct gas-solid carbonation is the simplest form of steel slag carbonation. It is diffusion controlled, which is similar to the natural weathering process, but with increased temperatures and higher CO_2 concentration for enhanced kinetics (DiGiovanni et al., 2024; Wang, Kim, et al., 2024). In direct gas-solid carbonation, CO_2 gas is reacted directly with the calcium and magnesium containing phases in the steel slag, thus requiring minimal usage of chemical reagents to move the reaction forward (Wang, Kim, et al., 2024).

Direct aqueous (wet) carbonation is a more complex method than the gas-solid method. It involves the use of an aqueous solution to enhance the dissolution of the CO_2 gas and leaching of reactive Ca and Mg ions from the steel slag (DiGiovanni et al., 2024). Although more complex, aqueous carbonation is less energy intensive since it can be operated using moderate temperatures and pressures. In addition, research estimates that direct aqueous carbonation can sequester up to three times more CO_2 than can be sequestered in dry carbonation (DiGiovanni et al., 2024).

Indirect carbonation

Indirect carbonation involves leaching the reactive ions, i.e., Ca^{2+} or Mg^{2+} from the slag prior to reacting them with CO_2 in an aqueous solution to form carbon precipitates. The

steel slag is usually treated for indirect carbonation using acidic and ammonium salt solutions (Zhao et al., 2025). This multi-step approach allows for more controlled reactions and potentially higher yields due to a high rate of ion extractions. However, it is relatively more complicated than the direct carbonation methods, and is more energy and cost intensive due to the addition of solvents and other reagent consumption (Wang, Wang, et al., 2024; Zhao et al., 2025). Figure 2 below shows the various methods of carbonation.

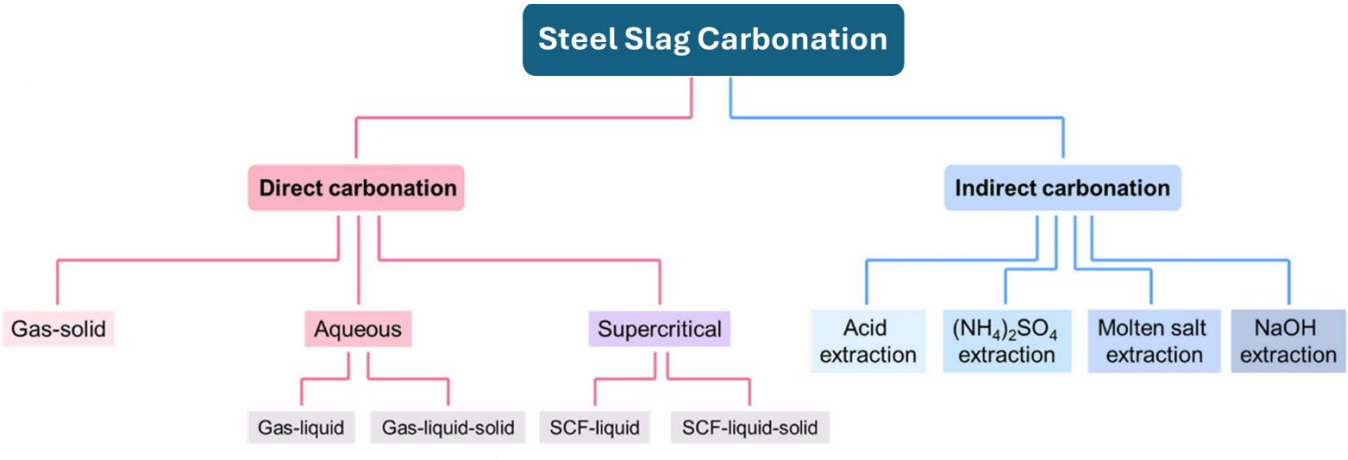


Figure 2. Methods for steel slag carbonation [Adapted from (Wang, Kim, et al., 2024)].

Each carbonation approach has unique advantages and tradeoffs, depending on the suitability to different industrial contexts or slag types, the target CO_2 removal levels, energy consumption and operational complexity. Table 1 below provides a summary of the steel slag carbonation methods.

Table 1. Steel slag carbonation methods, advantages and drawbacks.

Carbonation method	Reaction steps	Advantages	Drawbacks
Direct Carbonation			
Direct gas-solid (dry) carbonation	$CaO + CO_2 \rightarrow CaCO_3$ $MgO + CO_2 \rightarrow MgCO_3$ $Ca(OH)_3 + CO_{2\,(g)} \rightarrow CaCO_{3(s)} + H_2O_{(l)}$	• Relatively simple	• Typically slower • More energy intensive due to increased temperature to accelerate kinetics

Direct aqueous (wet) carbonation	Dissolution of calcium: $Ca_2SiO_{4(s)} + 4H^+_{(aq.)} \rightarrow 2Ca^{2+}_{(aq.)} + 2H_2O_{(l)} + SiO_{2(s)}$ Dissolution of CO_2 and subsequent conversion of carbonate species: $CO_{2(g)} + H_2O_{(l)} \rightarrow 2H^+ + CO_3^{2-}{}_{(aq.)}$ Precipitation of calcium carbonate and formation of the product layer of calcium carbonate: $Ca^{2+}_{(aq.)} + CO_3^{2-}{}_{(aq.)} \rightarrow CaCO_{3\,(s)}$	• Typically, faster reaction rate • Requires lower temperatures and pressures leading to lower energy intensity	• More complex than direct gas-solid carbonation due to aqueous environment
Indirect Carbonation	$(Ca, Mg)(CH_3COO)_2 + H_2O_{(l)} + CO_{2\,(g)} \rightarrow (Ca, Mg)CO_3 + 2CH_3COOH$	• More control over process kinetics • Higher yields	• Costly due to solvent use • More energy intensive due to solvent heating and use of additional pumps and fans

Feasibility of steel slag carbonation in industry

While promising, steel slag carbonation still faces technical hurdles that limit its scalability. For industrial feasibility, several key figures of merit must be optimized, including:

CO_2 uptake capacity: the total amount of CO_2 sequestered per unit of steel slag, which directly impacts process economics, particularly under potential future carbon credit/pricing schemes.

Reaction rate: indicates the speed of the carbonation reaction, encompassing the dissolution of CO_2 into solution, leaching of Ca^{2+} and Mg^{2+} ions, and their reaction with CO_2.

Energy intensity: reflects the overall energy demand of the process, contributed to by the reaction temperature and pressure requirements.

These metrics strongly influence the economic viability of steel slag carbonation and are primarily governed by process kinetics. As such, understanding and optimizing the kinetics is therefore essential for successful industrial implementation.

One major challenge in modelling the process kinetics stems from the heterogeneous nature of slag particles (Biava et al., 2024), which complicates efforts to generalize and scale predictive kinetic models. As a result, computational modeling for scale-up of steel slag carbonation remains limited. Nevertheless, several experimental studies have investigated steel slag carbonation and provided insights into the factors that influence process kinetics and provide opportunities for optimization.

The following section outlines the primary factors affecting process kinetics.

Key process kinetic parameters

As discussed earlier, careful control of the process kinetics increases the CO_2 sequestration capacity and informs industrial feasibility. The steel slag carbonation reaction undergoes three key phases, namely (1) dissolution of CO_2 into the reaction medium, (2) leaching of reactive ions in the steel slag into the solution, and (3) formation of the carbonated product layer. Experimental studies on steel slag carbonation have highlighted several factors that significantly influence the process kinetics, extent of the carbonation reaction, and the characteristics of the final carbonated products (Yu & Wang, 2011; Zhao et al., 2025).

Reaction temperature

The reaction temperature plays a pivotal role in the industrial feasibility of steel slag carbonation, as it impacts the energy demands of the process and ultimately the process costs (Elyasi Gomari et al., 2024; Yu & Wang, 2011). Experimental assessments have demonstrated that the temperature also plays a critical role in the efficiency and kinetics of the carbonation process. Tian et al. (2023) found temperature to be the most important factor influencing the rate of the direct gas-solid carbonation reaction (Tian et al., 2013).

Generally, increasing temperatures trend towards increasing the rate of reaction, though at the cost of increased energy input. This is because it enhances the thermal mobility of particles, promoting the dissolution of the reactive ions in the slag and increasing the rate of their reaction with CO_2 (Wang, Wang, et al., 2024; Yu & Wang, 2011). Yu et al., (2011) found that at elevated temperatures, the dissolution of reactive components intensifies,

resulting in greater availability of Ca^{2+} ions for carbonation and a three- to fivefold increase in the Ca^{2+} utilization (Yu & Wang, 2011).

However, studies reveal that the effects of temperature on the steel slag carbonation process are multifaceted. Results from experimental assessments demonstrate that temperature control is crucial, particularly in the aqueous carbonation route. While higher temperatures accelerate leaching of the reactive ions from steel slag, it simultaneously hampers CO_2 dissolution into aqueous solutions due to reduced gas solubility (DiGiovanni et al., 2024; Wang, Kim, et al., 2024).

Therefore, optimal temperatures for the slag carbonation must be identified and maintained. In aqueous systems, ideal temperature ranges lie between 20˚C and 100˚C, while dry gas-solid carbonation typically requires temperatures above 300˚C. Peng et al., (2020) observed optimal temperature for peak carbonation between 600°C and 700°C, suggesting that there's a threshold beyond which benefits plateau or reverse (Peng et al., 2020). This dual influence underscores the need for calibrated thermal management during carbonation to maximize efficiency without unintended drawbacks.

Particle size

The particle size is a critical parameter that directly impacts the surface area available for reaction during steel slag carbonation. Experimental studies have highlighted its strong influence on the CO_2 uptake rate, ranking it among the most impactful factors next to the reaction temperature.

Smaller particle size increases the surface area, which accelerates the reaction rate, enhances CO_2 absorption, and promotes a greater degree of carbonation (Tu et al., 2015; Wang, Kim, et al., 2024). To improve reactivity, mechanical milling or grinding of the steel slag is generally recommended (Biava et al., 2024), although this entails additional energy consumption.

It is important to note that different size fractions may exhibit varied chemical compositions, altering their reactivity. Therefore, if feasible, analysis of the compositions of various size fractions is recommended (Wang, Kim, et al., 2024).

Liquid to solid (L/S) ratio

This represents the volume of the liquid utilized per unit of steel slag. The L/S ratio serves as a key parameter in aqueous carbonation systems which typically use deionized water as the reaction medium. This ratio determines the availability of water essential for both the dissolution of CO_2 and the leaching of Ca^{2+} and Mg^{2+} ions for the carbonation reaction.

Research indicates that increasing the L/S ratio enhances the CO_2 sequestration capacity (Elyasi Gomari et al., 2024), likely due to improved CO_2 solubility. However, excessively high values dilute the reactive components and reduce the ion concentrations in solution, resulting in diminished carbonation performance (DiGiovanni et al., 2024). For example, Tu et al. (2015) reported that raising the L/S ratio from 5 g/g to 10 g/g increased the degree of carbonation, whereas further increasing it to 15 g/g led to reduced efficiency (Tu et al., 2015). These findings suggest that an optimal L/S ratio must be carefully identified and maintained to maximize reaction extent.

CO_2 pressure

The influence of the CO_2 pressure on the kinetics of steel slag carbonation remains an area of uncertainty. Thermodynamic principles predict that elevating the partial pressure of CO_2 should enhance its dissolution in the aqueous phase, thus improving carbonation. However, experimental findings on the effects of the CO_2 pressure vary considerably across studies (Ukwattage et al., 2017; Wang, Wang, et al., 2024). Some studies report negligible effects beyond certain pressure thresholds, while others observe significant improvements in the process kinetics at pressures exceeding 6 bar (DiGiovanni et al., 2024). Another study on the influence of the CO_2 pressure found no difference in total CO_2 sequestration between 1 MPa and 6 MPa but observed faster reaction times at higher pressures (Ukwattage et al., 2017).

These inconsistencies may be due to complex interdependencies with other process variables, such as the temperature, particle size, and liquid to solid ratio. For example, (Wang, Kim, et al., 2024) found that the extent to which CO_2 pressure accelerates reaction kinetics may depend on the rate-limiting step (slowest stage in the multi-step reaction) of the carbonation process.

Excessive pressure, however, should be avoided, as it is known to pose risks such as rapid precipitation of carbonated minerals, reduced interaction between slag and CO_2, and potential negative effects on the properties of the resulting carbonated materials.

Other factors

Other factors influencing the process kinetics include the process time, CO_2 concentration and volume, and slag composition.

The **reaction time** plays a role in determining the extent of the carbonation reaction. While sufficient time is required to achieve full reaction and increase the degree of carbonation (DiGiovanni et al., 2024; Wang, Kim, et al., 2024), minimizing the process time is desired to reduce the reactor size and improve the flowrate and overall process economics (Yu &

Wang, 2011). Therefore, careful control of the reaction time is needed to balance process efficiency and operational practicality.

The **CO_2 concentration** directly impacts the driving force for carbonation. Experimental data suggests that both low (10% v/v) and high (75% v/v) concentrations yield favorable results, indicating a nonlinear effect of the concentration (Yu & Wang, 2011). Conversely, studies have not observed a clear relationship between the total volume of CO_2 and the carbonation kinetics (DiGiovanni et al., 2024).

Finally, the **slag composition** is very relevant to the reaction kinetics, although difficult to standardize. Slag chemistry varies widely depending on the raw materials and operating conditions. Variability in the Ca- and Mg- content of steel slag affects reactivity. This variability in chemical compositions poses challenges for both characterization of slag and reproducibility of experimental results on the effects of slag composition on the carbonation kinetics (Biava et al., 2024). As such, limited research has been conducted to demonstrate which slag phases provide the highest CO_2 uptake. Therefore, further investigation is required to establish clearer relationships between slag phases and carbonation kinetics.

Table 2. Summary of factors influencing process kinetics.

Process Parameter	Definition and Units	Key Phase Impacted	Influence on kinetics
Temperature	Reaction temperature during carbonation (°C)	CO_2 dissolution, Leaching of reactive ions	Increasing temperature decreases CO_2 solubility but increases leaching rate and precipitation up to an optimum value
Pressure	Partial pressure of CO_2 in the reactor headspace (MPa)	CO_2 dissolution	Higher CO_2 pressure increases solubility in certain scenarios
Reaction time	Duration of carbonation reaction (min)	All phases	Longer reaction times increase carbonation degree until equilibrium

Liquid/Solid ratio (L/S)	Volume of liquid (usually water) per unit mass of slag (mL/g)	CO_2 dissolution, Leaching of reactive ions	Higher L/S enhances CO_2 dissolution but can dilute reactants if excessive
Slag particle size	Mean diameter of slag particles (μm)	Leaching of reactive ions, product precipitation	Smaller particle size increases surface area and enhances rate
CO_2 concentration	Mole percent of CO_2 in feed gas (%)	CO_2 dissolution	Higher concentration accelerates early-stage carbonation

Technical Assessment

Introduction to technical assessment

This technical assessment investigates the impact of key operational parameters on the reaction kinetics of steel slag carbonation and the associated CO_2 sequestration capacity. While multiple methods for steel slag carbonation exist, the assessment focuses on direct aqueous carbonation, in which solid steel slag reacts directly with CO_2 gas in a water-based medium—typically deionized water. This method has demonstrated the greatest promise in terms of kinetics and efficiency for industrial applications.

The assessment model was developed using data sourced from peer-reviewed scientific literature and industry publications spanning the years 2010 to 2025, with particular emphasis on experimental studies involving direct aqueous carbonation. The primary focus is on two critical metrics: the CO_2 uptake (mathematically described by the equation below) and the rate of the reaction (min) based on their critical importance in the industrial feasibility of slag carbonation as discussed earlier.

$$CO_2\ uptake\ \left(\frac{g\ CO_2}{kg\ steel\ slag}\right) = \frac{\omega CO_2(wt\%)}{1-\omega CO_2(wt\%)}\ x\ 1000$$

The technical assessment focuses on the influence of operational parameters on the process kinetics, namely the reaction temperature (°C) and the partial pressure (MPa) of

CO_2 over the solution. Other factors influencing the process kinetics have been qualitatively discussed in the prior sections.

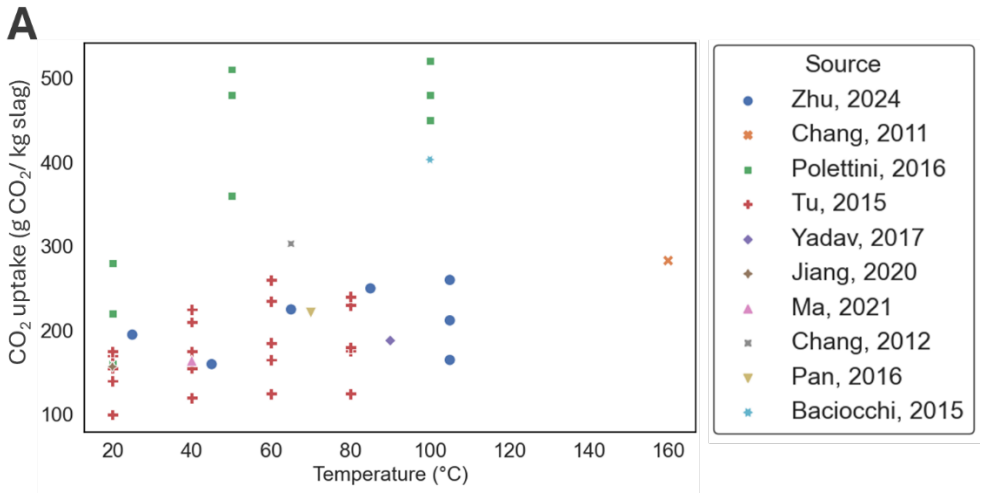
The studies assessed maintained pH ranging from 11-13, with the particle size ranging from 6 to 200 µm. The typical slag composition of the steel slag used in the assessment is shown in Table 3 below.

Table 3. Typical Slag Composition of steel slag used in the assessment.

Oxides	Composition (wt.%)
CaO	31 – 55 %
MgO	4.4 – 11 %
SiO_2	5.1 – 23 %
Fe_2O_3	10 – 37%

Effect of temperature on CO_2 uptake

The reaction temperature was the most consistently studied and influential parameter in the literature assessing steel slag carbonation kinetics. All studies reviewed for the assessment experimentally evaluated the impact of the temperature on the CO_2 uptake, highlighting its central role in process optimization. Figure 3 below illustrates the distribution of the reaction temperatures utilized across the studies. Detailed figures showing the distribution of the impacts of pressure and the reaction time are presented in the appendix.



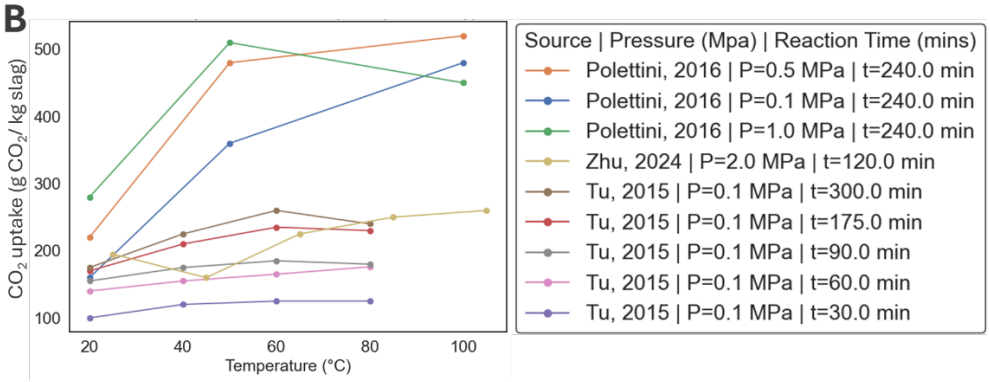


Figure 3. Distribution of operating temperatures across literature. Panel A: full range of temperatures assessed; Panel B: temperatures applied in continuous carbonation experiments. Legend indicates the associated pressure and reaction time for each temperature condition.

The temperature range explored spans from 20°C to 105°C, with a median temperature of 60°C. The maximum CO_2 uptake reported was 520 g CO_2/kg steel slag, which was achieved at 50°C . However, **60°C is recommended as the optimum temperature**, as it consistently yields high CO_2 uptake across varying reaction times and is typically applied under lower pressure conditions (0.1Mpa or ~1 atm).

To further analyze the effects of temperature on the carbonation performance, a predictive model was developed by synthesizing CO_2 uptake data from the most commonly tested temperature conditions: 20°C, 40 °C, 60 °C, and 80 °C, all under a fixed pressure of 0.1 MPa. This simplified approach was chosen to isolate the temperature variable, given its dominant influence on CO_2 uptake, and the prevalence of 0.1MPa as the reaction pressure applied in the literature. Figure 4 presents the resulting CO_2 uptake curve at varied temperatures.

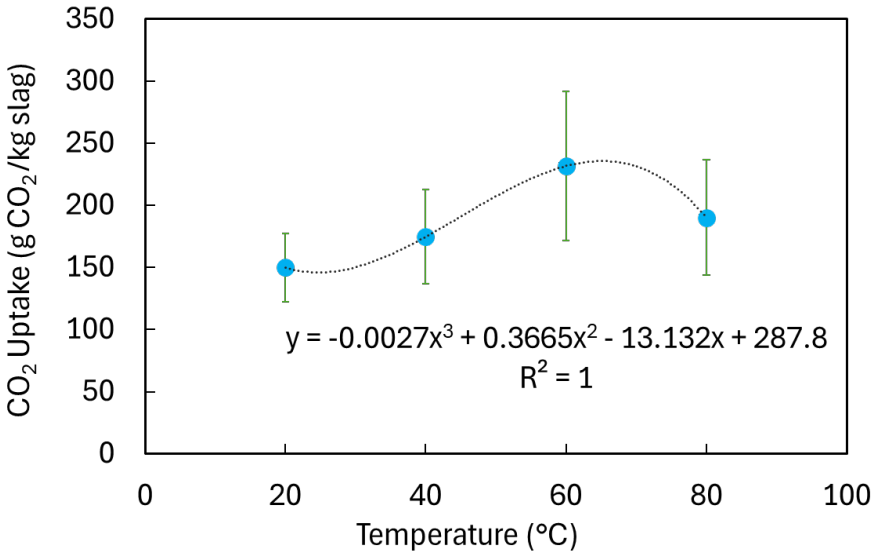


Figure 4. CO_2 uptake curve for steel slag carbonation at varied reaction temperatures. The line of best fit demonstrates a strong correlation, with an R^2 value of 1, indicating that the model is accurately aligned with the observed data. Error bars (green lines) represent the standard deviation of uptake values at each temperature, reflecting variability due to differing reaction times across studies.

At the optimum temperature of 60°C, the model predicts an average CO_2 uptake of 231.75g CO_2/kg steel slag, with a variability of approximately ±26%. The variability is attributed primarily to the differences in the duration for the carbonation reaction. In general, longer reaction times lead to increased carbonation, up to a threshold beyond which no further measurable CO_2 uptake is observed.

Conclusions and Recommendations

Steel slag carbonation is an emerging pathway to both valorize waste steel slag from the steel sector and contribute to its decarbonization by reacting CO_2 with steel slag. This study assessed the mechanisms of steel slag carbonation and its technical potential for carbon capture and sequestration. A comprehensive review of existing literature was conducted to examine the reaction kinetics, process parameters, and feasibility of scaling the technology for industrial use.

Among the various approaches, aqueous steel slag carbonation, in which solid slag reacts directly with CO_2 in a water-based medium, has demonstrated greatest promise in terms of reaction efficiency and scalability. Key parameters influencing the kinetics of this process

include temperature, pressure, particle size, and slag composition. Of these, temperature was identified as the most significant factor.

Optimal conditions for carbonation were found to be 50 – 60°C and 0.5 MPa, which can yield up to 236 g CO_2 sequestered per kg of steel slag within a reaction time of 4 – 5 hours.

However, the high variability in slag composition, driven by differences in steelmaking processes, raw materials and operational conditions, presents a challenge for predicting steel slag carbonation performance. This variability impacts the concentration of reactive phases, such as calcium and magnesium, which are critical to CO_2 uptake. Additionally, particle size plays a crucial role, with smaller particles offering greater surface area and higher reactivity, though each size fraction may have distinct chemical characteristics.

To support the industrial implementation of steel slag carbonation, the following recommendations are proposed:

I. Lab-scale experiments at Algoma: It is recommended for Algoma Steel to conduct targeted lab-scale experiments to:

- Characterize the specific steel slag composition and its variability across batches and size fractions.
- Optimize process parameters including temperature, pressure, particle size, and reaction time for maximum CO_2 uptake.
- Investigate the relationship between slag chemistry and carbonation efficiency, particularly the roles of Ca and Mg phases.
- Measure CO_2 uptake using gravimetric analysis to quantify sequestration potential under various conditions.

These experiments will provide the necessary data to tailor the carbonation process to Algoma's unique steel slag profile and support future scale-up efforts.

II. Environmental Impact Assessment: A life cycle assessment (LCA) is strongly recommended to evaluate the net environmental benefits of implementing steel slag carbonation. While current literature reports measurable CO_2 sequestration through this process, these figures typically reflect gross CO_2 removal—not accounting for emissions generated throughout the full life cycle. Without a detailed LCA, there is a risk that the process may result in net positive CO_2 emissions, particularly when considering energy-intensive steps such as slag grinding, temperature control, and material handling.

To ensure the technology delivers meaningful carbon mitigation, the LCA should aim to:

- Quantify emissions reductions and resource consumption across the entire process chain
- Assess energy requirements and sustainability trade-offs, including operational efficiency and energy sourcing
- Identify potential environmental risks or unintended consequences, such as secondary emissions or waste generation

The insights from the LCA will be critical for determining the true climate impacts of steel slag carbonation, and guiding decisions on its integration into steel production workflows in line with Algoma Steel's sustainability goals.

References

Algoma Steel. (2025). *2024 Sustainability Report*.

Biava, G., Depero, L. E., & Bontempi, E. (2024). Accelerated Carbonation of Steel Slag and Their Valorisation in Cement Products: A Review. *Spanish Journal of Soil Science*, *14*. https://doi.org/10.3389/sjss.2024.12908

DiGiovanni, C., Hisseine, O. A., & Awolayo, A. N. (2024). Carbon dioxide sequestration through steel slag carbonation: Review of mechanisms, process parameters, and cleaner upcycling pathways. *Journal of CO2 Utilization*, *81*, 102736. https://doi.org/10.1016/j.jcou.2024.102736

Elyasi Gomari, K., Rezaei Gomari, S., Hughes, D., & Ahmed, T. (2024). Exploring the potential of steel slag waste for carbon sequestration through mineral carbonation: A comparative study of blast-furnace slag and ladle slag. *Journal of Environmental Management*, *351*, 119835. https://doi.org/10.1016/j.jenvman.2023.119835

Grand View Research. (2025). *Canada Coated Steel Market Size & Outlook, 2024-2030*. https://www.grandviewresearch.com/horizon/outlook/coated-steel-market/canada

Khan, M. A., Powell, M., Tampier, M., Thorn, E., & Layzell, D. (2023). *Hydrogen and the Decarbonization of Steel Production in Canada: Reaching Economies of Scale*.

Kim, J., Sovacool, B. K., Bazilian, M., Griffiths, S., Lee, J., Yang, M., & Lee, J. (2022). Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options. *Energy Research & Social Science*, *89*, 102565. https://doi.org/10.1016/j.erss.2022.102565

Luo, Y., & He, D. (2021). Research status and future challenge for CO2 sequestration by mineral carbonation strategy using iron and steel slag. *Environmental Science and Pollution Research*, *28*(36), 49383–49409. https://doi.org/10.1007/s11356-021-15254-x

Natural Resources Canada. (2024). *Canada's GHG Emissions by Sector, End Use and Subsector – Including Electricity-Related Emissions*. https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=HB&sector=aaa&juris=ca&rn=3&page=0

OECD. (2025). *OECD Steel Outlook 2025*. OECD Publishing. https://doi.org/10.1787/28b61a5e-en

Peng, B., Yue, C., Li, Y., & Zhou, Y. (2020). Effects of different conditions on carbonation reaction of steel slag and kinetic analysis. *Bull. Ceram. Soc*, *39*(3562–3566).

Tian, S., Jiang, J., Chen, X., Yan, F., & Li, K. (2013). Direct Gas–Solid Carbonation Kinetics of Steel Slag and the Contribution to In situ Sequestration of Flue Gas CO_2 in Steel-Making Plants. *ChemSusChem*, *6*(12), 2348–2355. https://doi.org/10.1002/cssc.201300436

Tu, M., Zhao, H., Lei, Z., Wang, L., Chen, D., Yu, H., & Qi, T. (2015). Aqueous Carbonation of Steel Slag: A Kinetics Study. *ISIJ International*, *55*(11), 2509–2514. https://doi.org/10.2355/isijinternational.ISIJINT-2015-142

Ukwattage, N. L., Ranjith, P. G., & Li, X. (2017). Steel-making slag for mineral sequestration of carbon dioxide by accelerated carbonation. *Measurement*, *97*, 15–22. https://doi.org/10.1016/j.measurement.2016.10.057

Wang, S., Kim, J., & Qin, T. (2024). Mineral carbonation of iron and steel by-products: State-of-the-art techniques and economic, environmental, and health implications. *Journal of CO2 Utilization*, *81*, 102707. https://doi.org/10.1016/j.jcou.2024.102707

Wang, S., Wang, M., Liu, F., Song, Q., Deng, Y., Ye, W., Ni, J., Si, X., & Wang, C. (2024). A Review on the Carbonation of Steel Slag: Properties, Mechanism, and Application. *Materials (Basel, Switzerland)*, *17*(9). https://doi.org/10.3390/ma17092066

World Steel Association. (2025). *2025 World Steel in Figures*. https://worldsteel.org/about-us/who-we-are/

Yu, J., & Wang, K. (2011). Study on Characteristics of Steel Slag for CO_2 Capture. *Energy & Fuels*, *25*(11), 5483–5492. https://doi.org/10.1021/ef2004255

Zhao, Q., Liu, C., Mei, X., Saxén, H., & Zevenhoven, R. (2025). Research progress of steel slag-based carbon sequestration. *Fundamental Research*, *5*(1), 282–287. https://doi.org/10.1016/j.fmre.2022.09.023

Appendix

A. Pressure effects

Only about 20% of studies explicitly investigated the effects of pressure as an independent variable affecting CO_2 uptake. The pressure range assessed spans from 0.1 MPa to 4.8 MPa, with 0.1 MPa being the most commonly applied pressure condition.

The maximum CO_2 uptake of 520 g CO_2/kg steel slag was observed between 0.5 to 1 MPa pressure, suggesting that moderate pressure may be sufficient for enhanced carbonation efficiency. Figure A1 below highlights the distribution of reaction pressures employed across studies assessed.

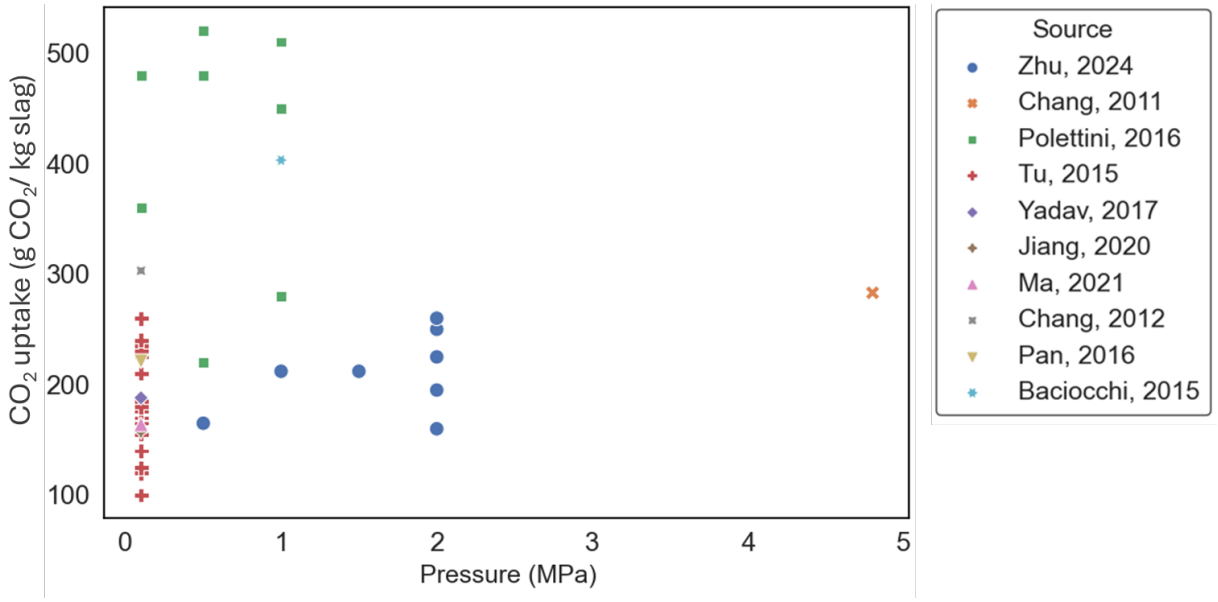


Figure A1. Distribution of reaction pressures (in MPa) applied for steel slag carbonation in literature.

B. Reaction time effects

The effect of the reaction time on steel slag carbonation was rarely studied in isolation. Only one study systematically explored its impact on the CO_2 uptake. Across the literature,

reaction durations ranged from 0.5 hours to 240 hours, with an average reaction time of 5 hours. **The highest CO_2 uptake was consistently observed between 4 – 5 hours**, beyond which additional reaction time did not yield significant improvements in the degree of carbonation observed. This suggests that there is a saturation point in the carbonation process, after which the reaction reaches equilibrium. Figure A2 displays the range of reaction times assessed and the corresponding CO_2 uptake values.

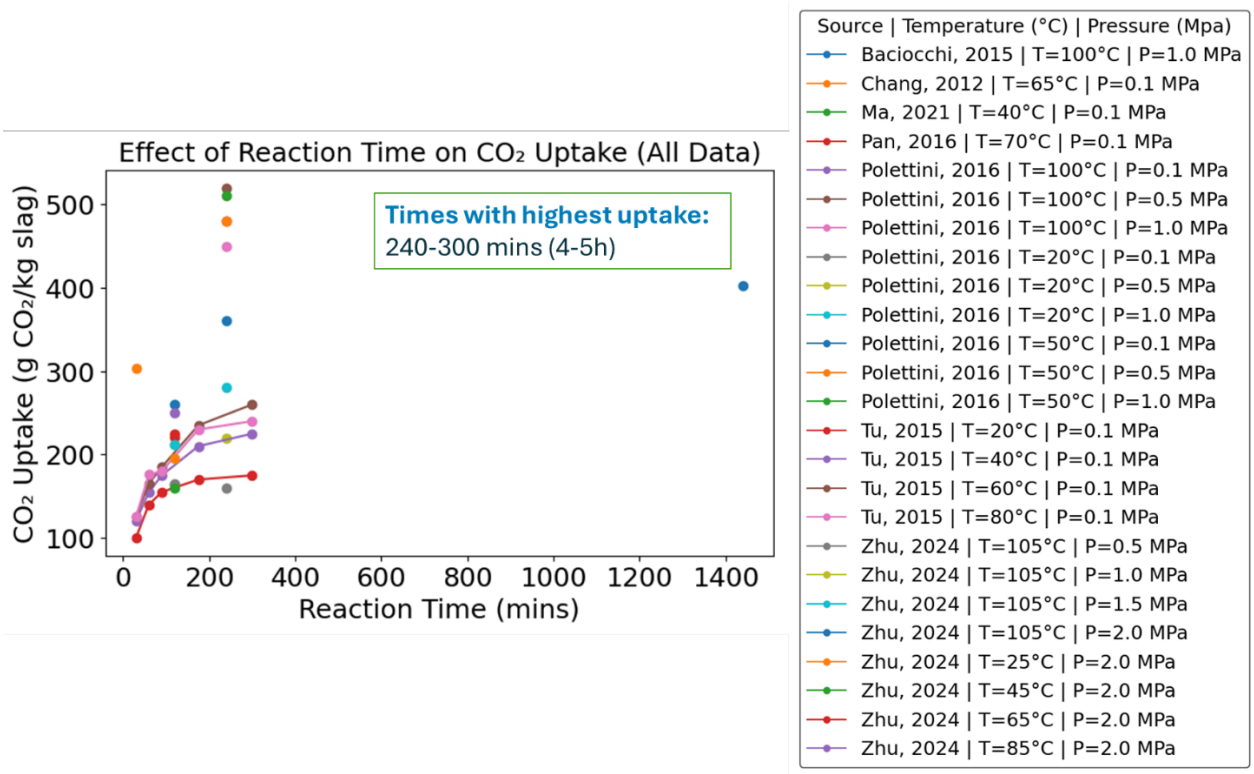


Figure A2. Range of reaction times assessed for steel slag carbonation in literature and corresponding CO_2 uptake values. Legend shows temperatures and pressures applied for a given reaction time.