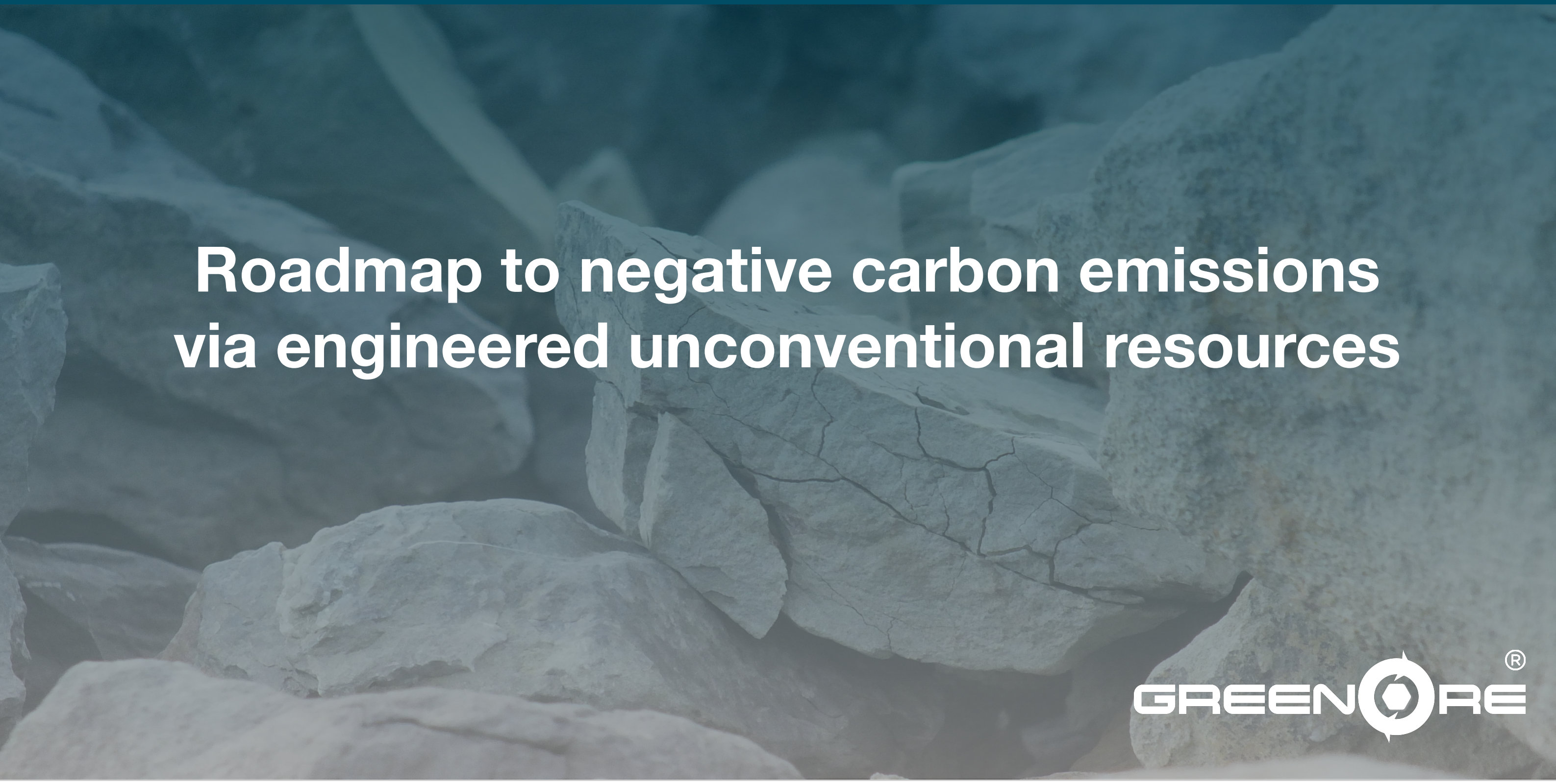


Roadmap to negative carbon emissions via engineered unconventional resources

Summary

Greenore couples carbon mineralization with unconventional resources which has enabled a diversified carbon utilization portfolio with the potential to achieve enormous and permanent carbon storage capacity. Greenore brings this unique carbon mineralization technology to an industrial scale with economic viability and is building a disruptive global green supply chain. In this white paper, the technology will be explained along with the lab-to-market routes and commercialization strategies.

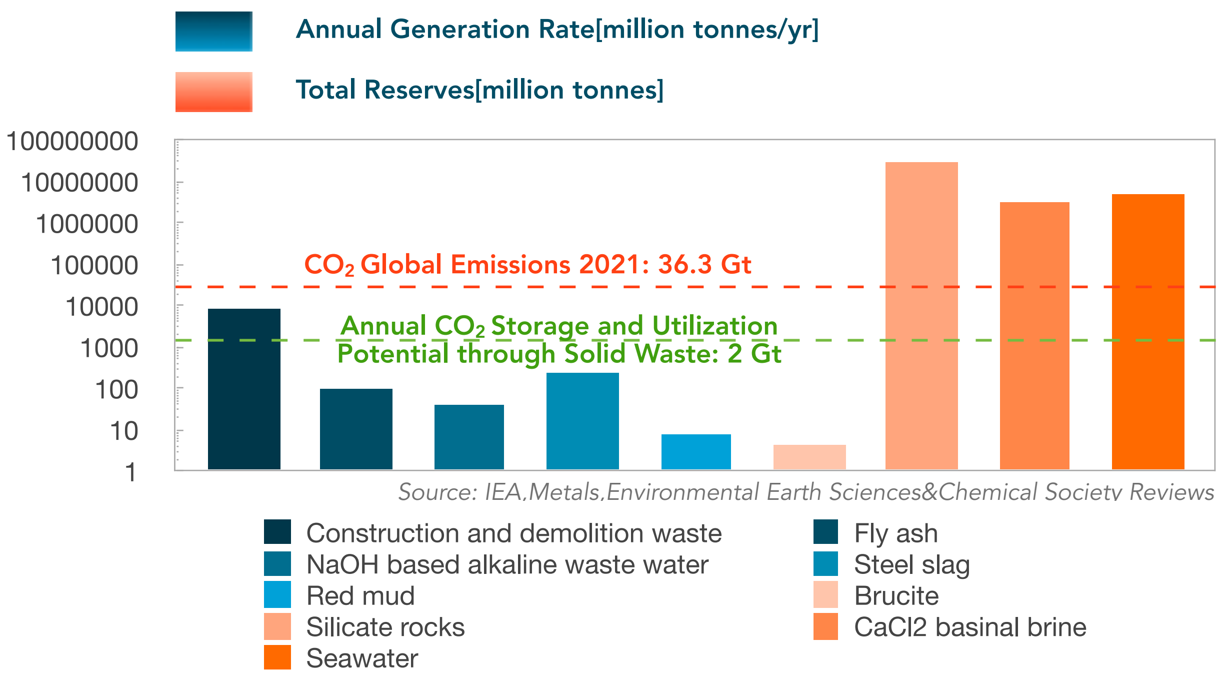
Introduction

It has been widely accepted that CCUS (Carbon Capture, Utilization and Storage) is a critical solution to addressing climate change caused by the increasing concentration of atmospheric CO_2[1,2], which has reached almost 420 ppm[3]. According to IEA, annual global CO_2 emissions are 36 Gt[4], necessitating urgent action and scalable solutions to address CO_2 emissions. CCUS technology is broadly applicable to reducing emissions by capturing carbon from flue gas[5–7], removing carbon from atmosphere[8–13], transforming the captured carbon to value-added products[14–17], and storing carbon permanently underground[18–20] or under deep ocean[21,22].

Carbon mineralization, as a key pathway in CCUS, can be conducted both in-situ manner[23,24] and ex-situ[23,25]. In an in-situ operation, CO_2 is directly injected underground to be stored in the form of stable carbonate after reacting with calcium-bearing and magnesium-bearing minerals.[23] On the other hand, ex-situ carbon mineralization mimics the natural weathering process above ground.[23] However, ex-situ carbon mineralization processes suffer from issues including slow reaction rates, mineral mining, material handling and associated costs.[24] Therefore, it has been envisioned that alkaline industrial solid wastes, such as steel slag, iron slag, fly ash, and cement waste, can be employed as an alternative source of feedstock to the ex-situ carbon mineralization process due to the material availability, reactivity and proximity to CO_2 point sources.[24,26] Meanwhile, numerous researchers have explored the mechanisms and optimization of industrial waste-based carbon mineralization processes by adjusting different key parameters.[27–32]

which can react with CO_2 to form stable calcium and magnesium carbonates in an accelerated manner compared to natural weathering processes.[28,31] As one of the largest carbon intensive industries, steel production industry generates 7% of the anthropogenic carbon emissions[33,34] with an annual production of almost 2 billion tonnes of crude steel per year[35]. On average, 400 kg of slag is produced per tonne of crude steel in blast furnaces while in electric arc furnaces, around 170 kg of slag is produced per tonne of crude steel.[36]

In China, approximately 300 million tonnes of steel slag is produced each year[37], while only 2/3 is utilized. Currently, China is faced with around 2 billion tonnes of legacy steel slag.[37]



CO_2 Storage and Utilization Potential

Under the philosophy of "picking the low-hanging fruit", Greenore grasps the synergy of carbon reduction and waste utilization by approaching carbon mineralization using steel slag. Steel slag, like other industrial solid wastes, is generally rich in CaO and MgO,

This legacy slag waste in China can be translated to a sequestration capacity of over 660 million tonnes of CO_2, in addition to the slag generated on an annual basis.

The potential of iron and steel slag for carbon fixation has also been proposed in UK[38], given that the amount of legacy iron and steel slag in the UK has been estimated to be over 190 million tonnes[39]. In addition, the characterization of iron and steel slag[40] and the study of their capacity in carbon sequestration[41] have also been investigated in the United States. Such high volume of slag around the globe can be served as a promising feedstock for carbon mineralization at the point of CO_2 emission to decarbonize essential industries such as steel and cement. By implementing slag-based carbon mineralization, environmental benefits such as reducing CO_2 emissions and solid waste disposal hazards can be achieved simultaneously.

Based on slag-based carbon mineralization, Greenore aims to further amplify the capacity of CO_2 sequestration by expanding the feedstock to other waste material such as fly ash, red mud, mine tailings, carbide slag, copper slag, etc. Ultimately, the utilization of Ca-bearing and Mg-bearing natural minerals will be realized through Greenore's technology in an economically viable manner at an industrial level.

Greenore has invented an economically-feasible and scalable technique to realize the reuse of industrial solid wastes and the fixation of carbon in an integrated manner which can target both carbon utilization as well as long term carbon storage. Greenore, under the enterprise mission "Rock science for a better planet", is equipped with a versatile technology portfolio for a comprehensive implementation of CCUS and decarbonization solution for industry.

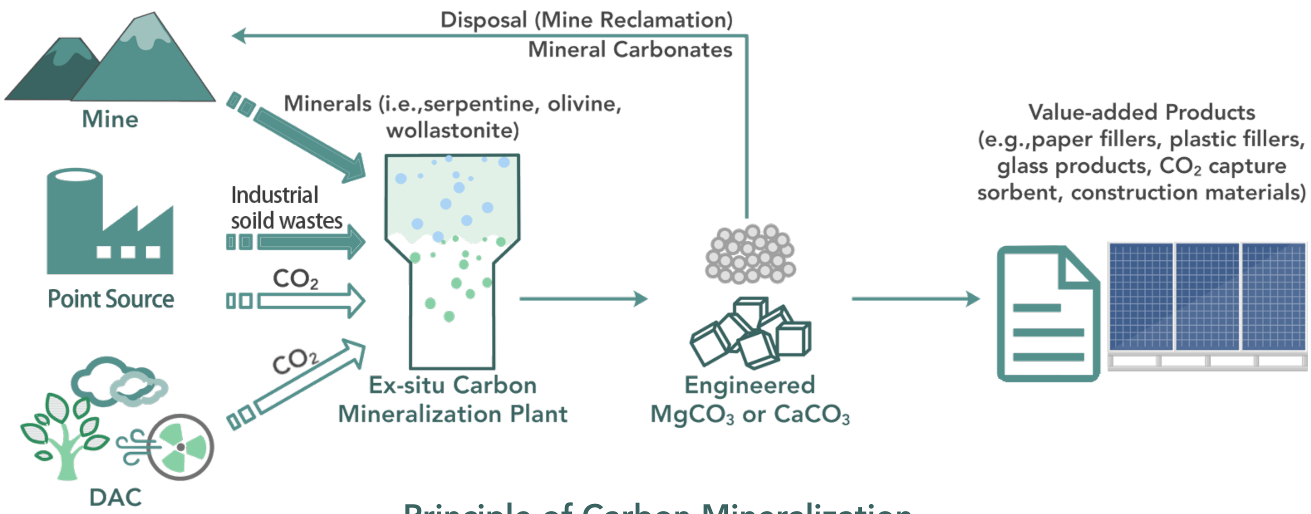
Rock science in slag-based CO_2 mineralization

The basic chemical reaction processes have been presented in equation 1-2, where the metal oxides in slag give rise to a higher reactivity of slag in carbon mineralization compared to natural minerals. The realization of this carbonation process involves two critical steps:

(1) The leaching of calcium and magnesium ions from slag into leachate as free ions or complexed ions.
(2) The crystallization and precipitation of calcium and magnesium carbonates.

$$Ca_xMg_{(1-x)}O + CO_2 \rightarrow Ca_xMg_{(1-x)}CO_3 \quad \text{Eqn. 1}$$

$$Ca_xMg_{(1-x)}SiO_3 + CO_2 \rightarrow Ca_xMg_{(1-x)}CO_3 + SiO_2 \quad \text{Eqn. 2}$$



Principle of Carbon Mineralization

Such processes can be carried out in a single step where a solid-liquid-gas reaction takes place.[28] A slag-DI water-CO_2 system can be constructed and a calcium carbonation efficiency of over 60% can be achieved at 19 bar CO_2 partial pressure and over 150 °C[28]. The formation of carbonate will affect the degree of leaching behaviors[27,28]. Low temperature of 40°C was also attempted but at an initial CO_2 pressure of 10-60 bar.[31]

In order to further enhance the reaction rate at ambient conditions and improve product quality control[42], a separate leaching step can be conducted prior to the carbonation step, leading to a two-step process. Multiple extraction solvents and chelating agents, such as HNO_3, HCl, acetic acid, and ammonia salt solutions,[30,42–46] have been studied on the leaching efficiency of calcium ions from slag, which is considered as one crucial rate-determining step for the reaction kinetics[43]. It is also discussed that the addition of base is needed for the subsequent precipitation process when acids are employed as the extraction solvents[46], which coincides with the pH swing methodology[20].

To facilitate the two-step carbonation process in an economical manner at an industrial level, Greenore's process utilizes a H_2O-CO_2 system as not only the extraction medium for steel slag but also as the carbon supplier for carbonation. The extraction step is assisted by a selection of proprietary catalysts that can be recovered after calcium precipitation. The cost of the highly-engineered catalysts is competitive at an industrial scale. In Greenore's process, an extraction efficiency of over 60% can be achieved within 30 minutes at ambient temperature in an economically viable way.

In the precipitation step, Greenore has invented a group of proprietary bases that can be compatible with the specific catalyst in the previous leaching step. In this way, the cost of waste water treatment can be controlled. High-purity calcium and magnesium carbonate can be fabricated with desired particle size, crystal shape, whiteness, opacity, etc.

It is also worth mentioning that such process can also be conducted in a one-step process depending on the requirements of product grade and the end-use of the carbonates. In most of the cases, one-step mineralization leads to products containing lower concentration of Ca/Mg carbonates which would be more suitable for constructional applications.

Faced with different sources of steel slag and other industrial wastes, such as fly ash, carbide slag, copper slag, etc., Greenore has designed a highly inclusive methodology, capable of tailoring carbon mineralization processes based on various industrial solid wastes such as mine tailings, construction waste and even natural minerals to achieve a negative carbon footprint. The process advantages are illustrated below.

1.Flexibility with CO_2 sources

Aiming at expanding carbon sequestration capacity, Greenore's process is flexible with the range and scope of CO_2 sources. The carbon source can be ambient air, flue gas from coal-fired power plants, flue gas from natural gas power plants, flue gas from steel plants, flue gas from cement plants, or any gas mixtures containing CO_2.

2.Carbon sequestration

Under the most conservative scenario, 0.2-0.25 tonnes of CO_2 can be sequestered per tonne of slag treated. Furthermore, if we count in the carbon credit and the indirect carbon emission reduction associated with the additional product manufacturing besides Greenore's process, the compounded CO_2 reduction per 1,000 kg steel slag will reach 1,248 kg based on SGS's Carbon Footprint Report.

3.Low cost and promising economic benefits

In addition to carbon storage, this technology can also produce high-quality products, off-setting the cost and emissions associated with a conventional production process. The use of a weak acid system and the recycling of reaction reagents further minimize the additional investment of materials.

4.Adaptability from wastes to minerals

Due to different sources of raw materials and iron/steel making techniques (e.g. BOF, EAF, etc.), the composition of slag varies among different plants. In order to adapt to each application, Greenore's process starts with a thorough analysis of the industrial waste samples. After matching the sample with Greenore's internal database, a tailored engineering process will be automatically determined. In this way, the scope of feedstocks that Greenore can process has been largely expanded, which includes but is not limited to steel slag, iron slag, copper slag, fly ash, carbide slag, etc. Relying on the mineralization industrial system and supply chain, this technology can be deployed at large scale as one of the tools to achieve low or even negative carbon emissions.

5.Tunability of end products

The Greenore's process turns wastes and carbon emissions into valuable resources as carbonates of different grades suitable for permanent storage and high value applications. By finely controlling the mineralization process, the end carbonate products exhibit enhanced performances in various fields such as paper making, paints, 3D printing, plastics, etc. With the use of Greenore's proprietary catalyst and base, the final products can be tuned into different sizes, morphologies, and other properties.

6.Recyclability of reagents

In order to further mitigate carbon emissions and improve water efficiency, the reagents in the entire process are recycled. Such design only requires a minimal amount of reagent refill to compensate for any loss during the reaction, keeping a material balance.

7.Scaling up

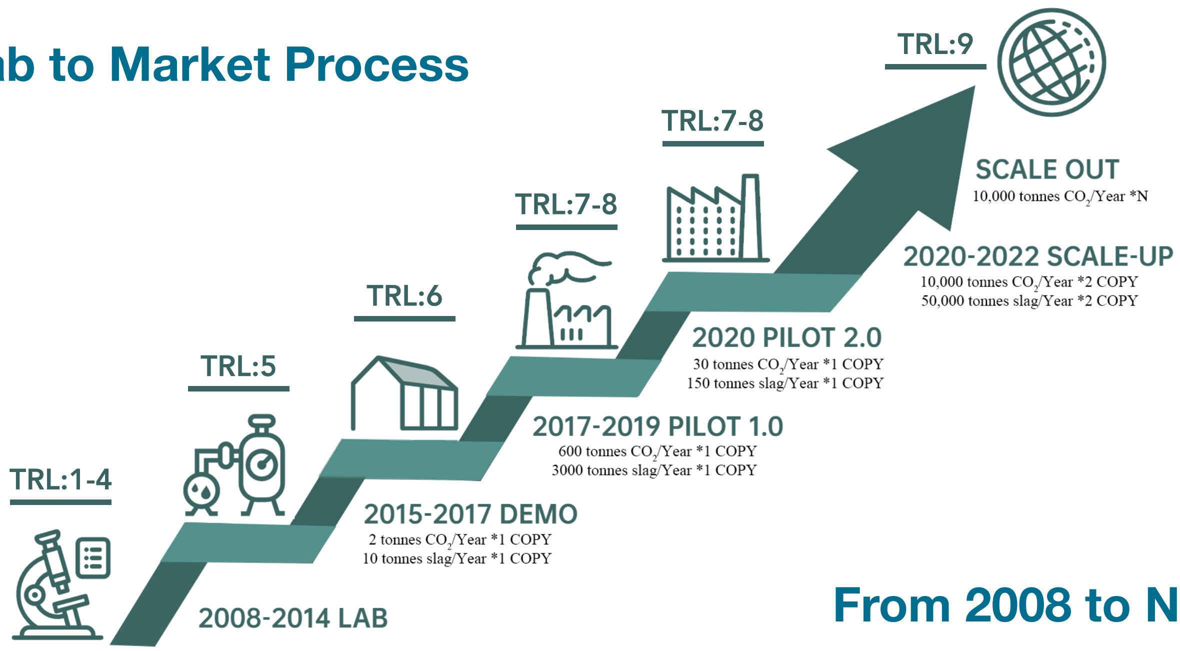
The Greenore's process is highly modularized. One typical processing module is able to treat 50,000 tonnes of slag per year or 10,000 tonnes of CO_2 per year, and multiple modules can meet the needed waste treatment capacity or carbon reduction target.

* A SimaPro calculation is also performed, showing a negative carbon emission for the process

Scaling up and diversified business portfolio

Greenore has turned a green concept into reality. As a spin-off from Columbia University in the City of New York, the slag carbonation process has been tested from lab beaker to a 3,000 tonne-slag/yr pilot unit. Two scaled-up units of a 50,000 tonne-slag/yr capacity are to be in operation starting Q4, 2022. Greenore's technology has been proven effective and scalable.

Lab to Market Process



From 2008 to Now

With a current economic benefit of 29% gross margin of the current implementation, many renowned corporations have formed a strong alliance with Greenore to pursue carbon mineralization while transforming waste into valuable resources. Corporations, such as Baotou Steel Group, Harsco, TATA steel, BAOWU, POSCO, CRH group, have partnered with Greenore at different commercialization stages. Meanwhile, the industrial scaling-up of Greenore has also been backed up by fundamental research both within the internal R&D department and through collaborations with universities, such as Columbia University, Tsinghua University and Shanghai University.

In addition to the proven technology of carbon mineralization to transform waste into value-added resources, Greenore also has a valuable technology portfolio in carbon capture, which can be well integrated with the carbonation process. Furthermore, an innovative recycling technology of lithium-ion batteries has also been proposed by Greenore using similar weak acid system accompanied by proprietary catalysts.

Business Model

In general, Greenore employs two business models for project implementations. BOO (Build, Own, Operate) model is preferred in centralized markets. On the other hand, a Licensing + Technical service model is also adopted for market economy driven regions. Meanwhile, Greenore is also open to customized collaboration models to better facilitate the commissioning of the carbon mineralization process using Greenore's technology. Greenore is dedicated to create win-win CCUS collaboration opportunities.

Conclusions

Greenore has enhanced the scope and capacity of carbon sequestration by offering an innovative and scalable solution to carbon mineralization to transform waste liabilities into value-added products. Such coupling brings a negative carbon technology solution to carbon intensive industries and solves solid waste disposal issues and associated environmental pollution problems. In addressing the complexity of various feedstocks, Greenore has designed a tunable process with a proven record of scale up and commercialization. Greenore is dedicated to building an industry and business ecosystem for the ultimate carbon negative goal built upon industrial solid waste-based carbon mineralization in this and coming decades. With the support from governmental policies, financial incentives, economic opportunity, and corporate motives, Greenore is accelerating CCUS technology implementation worldwide to deliver a negative carbon economy.

References

[1] Climate Change 2022: Mitigation of Climate Change. https://www.ipcc.ch/report/ar6/wg3/

[2] Pacala S, Socolow R. Stabilization Wedges: the Climate Problem for the Next 50 Years with Current Technologies. *Science*. 2004;305(5686): 968-972. doi:10.1126/science.1100103

[3] Daily CO_2. https://www.co2.earth/daily-co2

[4] Global CO_2 emissions rebounded to their highest level in history in 2021 - News. IEA. https://www.iea.org/news/global-co2-emissions-rebounded-to-their-highest-level-in-history-in-2021

[5] Wang X, Song C. Carbon Capture From Flue Gas and the Atmosphere: A Perspective. In: *Frontiers in Energy Research*. ; 2020. doi:10.3389/fenrg.2020.560849

[6] Schäffer A, Brechtel K, Scheffknecht G. Comparative study on differently concentrated aqueous solutions of MEA and TETA for CO_2 capture from flue gases. *Fuel*. 2012;101:148-153. doi:10.1016/j.fuel.2011.06.037

[7] Mangalapally HP, Notz R, Hoch S, et al. Pilot plant experimental studies of post combustion CO_2 capture by reactive absorption with MEA and new solvents. *Energy Procedia*. 2009;1(1):963-970. doi:10.1016/j.egypro.2009.01.128

[8] Keith DW. Why Capture CO_2 from the Atmosphere? *Science*. 2009;325(5948):1654-1655. doi:10.1126/science.1175680

[9] Keith DW, Ha-Duong M, Stolaroff JK. Climate Strategy with CO_2 Capture from the Air. *Clim Change*. 2006;74(1):17-45. doi:10.1007/s10584-005-9026-x

[10] Azarabadi H, Lackner KS. A sorbent-focused techno-economic analysis of direct air capture. *Appl Energy*. 2019;250:959-975. doi:10.1016/j.apenergy.2019.04.012

[11] Lackner KS. The thermodynamics of direct air capture of carbon dioxide. *Energy*. 2013;50:38-46. doi:10.1016/j.energy.2012.09.012

[12] Gebald C, Wurzbacher JA, Tingaut P, Steinfeld A. Stability of Amine-Functionalized Cellulose during Temperature-Vacuum-Swing Cycling for CO_2 Capture from Air. *Environ Sci Technol*. 2013;47(17): 10063-10070. doi:10.1021/es401731p

[13] Gebald C, Wurzbacher JA, Tingaut P, Zimmermann T, Steinfeld A. Amine-Based

Zimmermann T, Steinfeld A. Amine-Based Nanofibrillated Cellulose As Adsorbent for CO_2 Capture from Air. *Environ Sci Technol.* 2011;45(20): 9101-9108. doi:10.1021/es202223p

[14] Jones WD. Carbon Capture and Conversion. *J Am Chem Soc.* 2020;142(11):4955-4957. doi:10. 1021/jacs.0c02356

[15] Ding M, Flaig RW, Jiang HL, Yaghi OM. Carbon capture and conversion using metal–organic frameworks and MOF-based materials. *Chem Soc Rev*. 2019;48(10):2783-2828.

[16] Alper E, Yuksel Orhan O. CO_2 utilization: Developments in conversion processes. *Petroleum*. 2017;3(1):109-126. doi:10.1016/j.petlm.2016.11.003

[17] Song C. CO_2 Conversion and Utilization: An Overview. In: *CO_2 Conversion and Utilization*. Vol 809. ACS Symposium Series. American Chemical Society; 2002:2-30. doi:10.1021/bk-2002-080 9.ch001

[18] Lackner KS. A Guide to CO_2 Sequestration. *Science*. 2003;300(5626):1677-1678. doi:10.1126/ science.1079033

[19] Bickle MJ. Geological carbon storage. *Nat Geosci.* 2009;2(12):815-818. doi:10.1038/ngeo687

[20] Park AHA, Fan LS. CO_2 mineral sequestration: physically activated dissolution of serpentine and pH swing process. *Chem Eng Sci.* 2004;59(22): 5241-5247. doi:10.1016/j.ces.2004.09.008

[21] Goldberg DS, Takahashi T, Slagle AL. Carbon dioxide sequestration in deep-sea basalt. *Proc Natl Acad Sci*. 2008;105(29):9920-9925. doi:10.1073/ pnas.0804397105

[22] House KZ, Schrag DP, Harvey CF, Lackner KS. Permanent carbon dioxide storage in deep-sea sediments. *Proc Natl Acad Sci*. 2006;103(33): 12291-12295. doi:10.1073/pnas.0605318103

[23] Romanov V, Soong Y, Carney C, Rush GE, Nielsen B, O'Connor W. Mineralization of Carbon Dioxide: A Literature Review. *ChemBioEng Rev*. 2015;2(4):231-256. doi:10.1002/cben.201500002

[24] Sanna A, Uibu M, Caramanna G, Kuusik R, M. Maroto-Valer M. A review of mineral carbonation technologies to sequester CO_2. *Chem Soc Rev*. 2014;43(23):8049-8080. doi:10.1039/C4CS00035H

[25] Kelly KE, Silcox GD, Sarofim AF, Pershing DW. An evaluation of ex situ, industrial-scale, aqueous CO_2 mineralization. *Int J Greenh Gas Control*. 2011; 5(6):1587-1595. doi:10.1016/j.ijggc. 2011.09.005

[26] Rim G, Roy N, Zhao D, et al. CO_2 utilization in built environment via the P_{CO_2} swing carbonation of alkaline solid wastes with different mineralogy. *Faraday Discuss.* 2021;230(0):187-212. doi:10.1039/ D1FD00022E

[27] Huijgen WJJ, Comans RNJ. Carbonation of Steel Slag for CO_2 Sequestration: Leaching of Products and Reaction Mechanisms. *Environ Sci Technol*. 2006;40(8):2790-2796. doi:10.1021/es052534b

[28] Huijgen WJJ, Witkamp GJ, Comans RNJ. Mineral CO_2 Sequestration by Steel Slag Carbonation. *Environ Sci Technol.* 2005;39(24):9676-9682. doi:10.1021/ es050795f

[29] Azdarpour A, Asadullah M, Mohammadian E, Hamidi H, Junin R, Karaei MA. A review on carbon dioxide mineral carbonation through pH-swing process. *Chem Eng J*. 2015;279:615-630. doi: 10.1016/j.cej.2015.05.064

[30] Zhao H, Park Y, Lee DH, Park AHA. Tuning the dissolution kinetics of wollastonite via chelating agents for CO_2 sequestration with integrated synthesis of precipitated calcium carbonates. *Phys Chem Chem Phys.* 2013;15(36):15185-15192. doi:10.1039/C3CP52459K

[31] Ukwattage NL, Ranjith PG, Li X. Steel-making slag for mineral sequestration of carbon dioxide by accelerated carbonation. *Measurement*. 2017;97: 15-22. doi:10.1016/j.measurement. 2016.10.057

[32] Pan SY, Chung TC, Ho CC, Hou CJ, Chen YH, Chiang PC. CO_2 Mineralization and Utilization using Steel Slag for Establishing a Waste-to-Resource Supply Chain. *Sci Rep*. 2017;7(1):17227. doi:10. 1038/s41598-017-17648-9

[33] Holappa L. A General Vision for Reduction of Energy Consumption and CO_2 Emissions from the

Steel Industry. *Metals*. 2020;10(9):1117. doi:10.3390/met10091117

[34] Kim Y, Worrell E. International comparison of CO_2 emission trends in the iron and steel industry. *Energy Policy*. 2002;30(10):827-838. doi:10.1016/S0301-4215(01)00130-6

[35] Total production of crude steel. worldsteel.org. Accessed May 18, 2022. https://worldsteel.org/steel-by-topic/statistics/annual-production-steel-data/P1_crude_steel_total_pub/CHN/IND/WORLD_ALL

[36] Fact sheets. worldsteel.org. https://worldsteel.org/publications/fact-sheets/

[37] Chinese startup tackles 2bn tons of slag with new technology. Nikkei Asia. https://asia.nikkei.com/Business/36Kr-KrASIA/Chinese-startup-tackles-2bn-tons-of-slag-with-new-technology

[38] Pullin H, Bray AW, Burke IT, et al. Atmospheric Carbon Capture Performance of Legacy Iron and Steel Waste. *Environ Sci Technol*. 2019;53(16):9502-9511. doi:10.1021/acs.est.9b01265

[39] Riley AL, MacDonald JM, Burke IT, et al. Legacy iron and steel wastes in the UK: Extent, resource potential, and management futures. *J Geochem Explor*. 2020;219:106630. doi:10.1016/j.gexplo.2020.106630

[40] Piatak NM, Seal RR, Hoppe DA, Green CJ, Buszka PM. Geochemical Characterization of Iron and Steel Slag and Its Potential to Remove Phosphate and Neutralize Acid. *Minerals*. 2019;9(8):468. doi:10.3390/min9080468

[41] Stolaroff JK, Lowry GV, Keith DW. Using CaO- and MgO-rich industrial waste streams for carbon sequestration. *Energy Convers Manag*. 2005;46(5):687-699. doi:10.1016/j.enconman.2004.05.009

[42] Eloneva S, Teir S, Revitzer H, et al. Reduction of CO_2 Emissions from Steel Plants by Using Steelmaking Slags for Production of Marketable Calcium Carbonate. *Steel Res Int*. 2009;80(6):415-421. doi:10.2374/SRI09SP028

[43] Kakizawa M, Yamasaki A, Yanagisawa Y. A new CO_2 disposal process via artificial weathering of calcium silicate accelerated by acetic acid. *Energy*. 2001;26(4):341-354. doi:10.1016/S0360-5442(01)00005-6

[44] Tinchana S, Chungsiriporn J, Bunyakan C. Leaching of steelmaking slag using acetic acid solution and deionized water for CO_2 sequestration. In: The 10th International PSU Engineering Conference. ; 2012.

[45] Bao W, Li H. Synthesis of Aragonite Superstructure from Steelmaking Slag via Indirect CO_2 Mineral Sequestration. *Int J Mater Metall Eng*. 2012;6(5):496-502.

[46] Eloneva S, Teir S, Salminen J, Fogelholm CJ, Zevenhoven R. Steel Converter Slag as a Raw Material for Precipitation of Pure Calcium Carbonate. *Ind Eng Chem Res*. 2008;47(18):7104-7111. doi:10.1021/ie8004034