

Report Highlights

- To avoid dangerous climate change, deployment of negative emissions technology is now essential.
- The umbrella term ‘carbon capture and storage & utilisation’ encompasses a suite of technologies for preventing CO₂ from entering the atmosphere.
- Mineral Carbonation is one example of CCSU where CO₂ is stored in the form of inert carbonate rock.
- Mineral Carbonation is already a commercial process, producing building materials and high value chemical products.
- With policy support and appropriate investment, Mineral Carbonation could scale to become a large industry, storing a significant volume of emissions, particularly from small industrial emitters who may not find geological CO₂ storage practical.
- CCSU - both geologic storage and Mineral Carbonation - requires urgent policymaker attention in order to tackle the planet’s greenhouse gas emissions.

About Sandbag

Sandbag is a UK-based not-for-profit think tank conducting research and campaigning for environmentally effective climate policies.

Our research focus, since our establishment in 2008, includes reform of the EU Emissions Trading Scheme, the EU 2020 and 2030 climate & energy packages, Carbon Capture & Storage/Utilisation, and the phase-out of old coal in Europe.

More information at sandbag.org.uk

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“Carbon dioxide capture and storage by mineral carbonation is a technology that can potentially sequester billions of tonnes of carbon dioxide per year.”

-Sanna et al., 2012

Overview

Mineral carbonation is one of a suite of technologies that fall under the umbrella term '**carbon capture storage & utilisation**' (CCSU). Mineral carbonation captures and stores CO₂ through its reaction with a mineral feedstock to form an inert carbonate rock, similar to limestone. CCS technologies are likely to be a crucial part of any low-carbon future, with the IPCC estimating that meeting global emissions targets will be 138% more expensive without CCS.¹

Currently, the most technologically mature CCS technology is **geological storage**, wherein CO₂ is removed from the exhaust gases of an industrial or power plant, then compressed and transported (via ship or pipeline) to be injected into an underground location such as a disused hydrocarbon reservoir or saline aquifer. Geological storage is considered to be 'economically feasible' ([IPCC CCS Report, 2005](#)²) and is already in commercial use for enhanced oil recovery at a small number of sites. In order to meet future demand for storage it is vital that investment in the appraisal of geological storage sites continues.

Just as the term renewable energy refers to a group of technologies with differing attributes, CCSU denotes a broad suite of technologies rather than a single solution. Achieving rapid decarbonisation of energy-intensive systems at lowest cost requires the development of a **diverse range of technologies**. This will avoid the risks associated with dependence on a single technology, encourage competition for investment and allow for the broadest possible deployment. The use of a diverse range of technologies is widely accepted for low-carbon electricity generation: the same is true for the capture of CO₂ emissions.

Mineral carbonation is a technology that can compliment geological storage in sequestering anthropogenic carbon emissions. To meet emissions targets CCSU technologies must be rolled out on a large scale and the diversity of CO₂-producing plants means that a variety of technologies are necessary. Because CCSU requires significant investment in infrastructure to scrub, compress and transport CO₂ for storage, mineral carbonation may in some cases be cheaper and more appropriate than geological storage, particularly for smaller plants ([Sanna et al, 2012](#)³). Mineral carbonation can in some cases use raw waste gas, rather than pure CO₂, which greatly increases the simplicity of the process and reduces scrubbing costs. Furthermore, mineral carbonation can be used to neutralise an array of harmful industrial wastes, producing useful and profitable products in the process.

There are a small number of existing commercial applications of mineral carbonation, but truly scalable mineral carbonation processes are still technologically in their infancy. In other words, further research is essential if mineral carbonation processes can contribute on a large scale to carbon sequestration. However, the technology and business model is already proven to work without the need for public finance. Importantly, due to the long-term stability and value of mineral carbonation products, it could have greater public acceptability than geological storage (especially where geological storage is linked to Enhanced Oil Recovery). Therefore, we conclude that, mineral carbonation technologies should be supported in parallel with geological storage, and that doing so will result in increased and accelerated low cost decarbonisation.

¹ IPCC (2014) "Table SPM.2, Summary for Policymakers."

² IPCC (2005) "Carbon Dioxide Capture and Storage," Cambridge University Press, Cambridge, 2005.

³ A. Sanna, M. R. Hall and M. Maroto-Valer, (2012) "Post-processing pathways in carbon capture and storage by mineral carbonation (CCSM) towards the introduction of carbon neutral materials," *Energy & Environmental Science*, vol. 5, pp. 7781-7796.

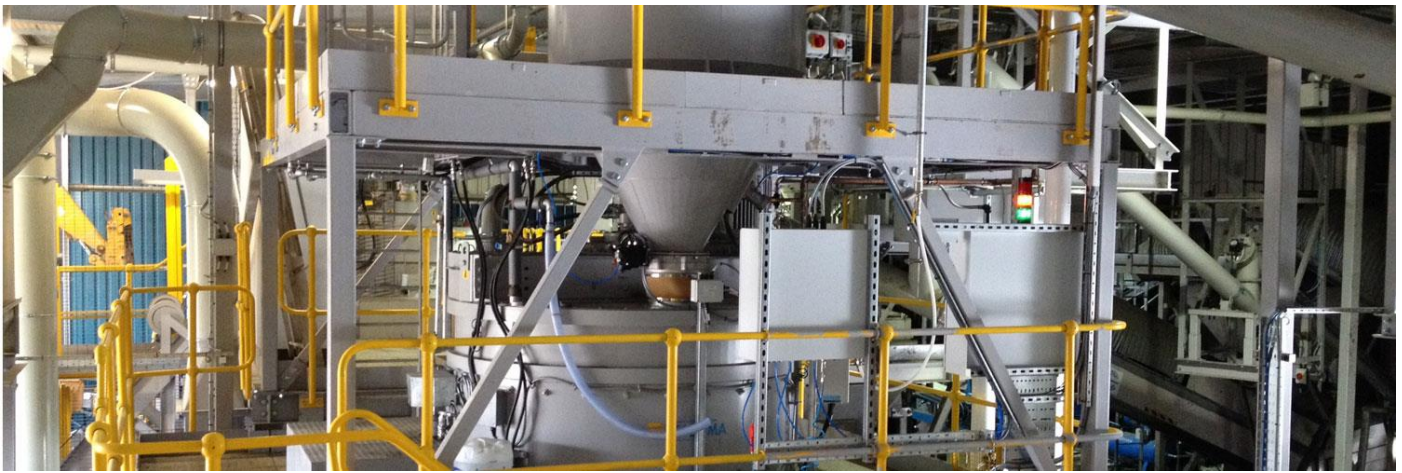


Figure 1 Mineral Carbonation at a Carbon8 plant near Cambridge, UK

What is Mineral Carbonation?

The transformation of minerals (metal oxides) to metal carbonates through reaction with carbon dioxide is a natural chemical weathering process that occurs without human intervention over geological timescales. Most of Earth's carbon is sequestered naturally in carbonate rocks such as limestone (predominantly calcium carbonate). This process can also be mechanically accelerated to sequester anthropogenic carbon dioxide, either below ground (in situ) or above ground (ex situ).

In situ mineral carbonation involves injecting compressed and purified carbon dioxide into geological formations located at 700m or more below ground level. Storage sites include depleted oil fields or saline aquifers and are ideally naturally rich in alkaline minerals to encourage the slow formation of carbonate rocks and hence permanent sequestration of the carbon ([IPCC CCS Report, 2005](#)). This process has a great deal in common with conventional geological storage of CO₂ in oil and gas reservoirs in terms of its process.

Ex situ mineral carbonation takes place above ground through accelerating the chemical reaction between a metal oxide feedstock and carbon dioxide, resulting in a carbonate product. This basic process can be carried out using a wide range of materials for feedstock and yields inert products in which the carbon dioxide is permanently sequestered ([RSC Review Paper, 2014](#)⁴). There are a number of commercial plants in operation which use versions of the mineral carbonation process to convert feed stocks such as incinerator ash, cement bypass dust, steelmaking sludge and other waste streams into carbon-negative concrete blocks ([Carbon8](#)), carbonate cement ([Calera](#)) and high value chemical products ([Skyonic](#)).

The process of mineral carbonation of waste streams is already profitable at a small scale thanks to the gate fees received for disposal of these waste streams. Deployment on a scale that would result in globally-significant carbon dioxide reductions may involve using mined rocks rich in minerals such as olivine and serpentine as feedstock. Both minerals are available in abundance and have been demonstrated to be feasible ([RSC Review Paper, 2014](#)). Mine tailings offer another potential source of pre-pulverised mineral feedstock. However, extraction and transportation of minerals for the carbonation process may offset some of the environmental benefits of the mineralisation process.

⁴ A. Sanna, M. Uibu, G. Caramanna, R. Kuusik and M. Maroto-Valer (2014) "A review of mineral carbonation technologies to sequester CO₂," *Chem Soc Rev*, no. 43, p. 8049.

The key advantages and drawbacks of large-scale mineral carbonation as a complementary form of CCS by geological storage (GS) are outlined in Table 1.

ADVANTAGES	DRAWBACKS
More truly permanent	Currently less technologically advanced
Requires no long-term monitoring. Testing of mineral carbonation products shows that toxic chemicals are not released	Though an exothermic chemical reaction process will sometimes be more energy-intensive than GS due to need for high temperatures and/or pressurisation (RSC Review Paper , 2014)
Capture and storage is possible using a single process – therefore could be simpler and cheaper (Sanna et al , 2012)	Requires transportation and materials handling of feedstock and products
Creates a useable product. Likelihood for better public acceptability (Wennersten et al , 2014 ⁵)	On a very large scale, could require disposal of products in mine reclamation, ocean disposal or land filling

Table 1 - Comparison of Mineral Carbonation and Geological Storage

How large is the potential of Mineral Carbonation?

Industrial Wastes to Construction Products and High Value Chemicals

Although commercial mineral carbonation plants already exist – including those that neutralise environmentally harmful waste – existing regulations around the transportation of wastes limit the scale of these operations. Industrial wastes that are suitable feedstocks include steelmaking slags, cement kiln dust and municipal solid waste incinerator ash ([Pan et al](#), 2012⁶). Certain types of mine tailings can also be used to capture CO₂ through mineral carbonation, such as asbestos, nickel and red mud (a by-product of bauxite ore mining for aluminium extraction). However, the readiness of companies to process these wastes is limited by access and restrictions on transporting of hazardous wastes, the quantity of waste available and the geography of the supply network. Annual worldwide production of industrial alkaline waste streams could sequester between 300-200Mt CO₂ ([Sanna et al](#), 2012), with additional CO₂ utilised in high-value chemical products.

A number of organisations are exploring the potential of olivine minerals to absorb large quantities of CO₂ from the atmosphere, a process known as accelerated weathering. One example is Dutch enterprise greenSand whose ground olivine products have the dual purpose of fertilising magnesium-deficient soils while passively absorbing CO₂ from the atmosphere. Research carried out by SmartStones suggests the carbon intensity of mining, crushing and spreading the olivine is more than compensated for by the subsequent CO₂-absorbing reactions which ostensibly take place at faster rates than unmined olivine since crushing the rock greatly increases the rock's reactive surface area ([Schuiling, 2010⁷](#)).

⁵ R. Wennersten, Q. Sun and H. Li (2014) "The future potential for Carbon Capture and Storage in climate change mitigation – an overview from perspectives of technology, economy and risk," *Journal of Cleaner Production*, pp. 1 – 13.

⁶ S.-Y. Pan, E. Chang and P.-C. Chiang (2012) "CO₂ Capture by Accelerated Carbonation of Alkaline Wastes: A Review on Its Principles and Applications," *Aerosol and Air Quality Research*, vol. 12, pp. 770-791.

⁷ O. Shuiling (2010) "Olivine: Against Climate Change and Ocean Acidification" (conference presentation).

<http://www.smartstones.nl>

Other companies have sought ways of replacing carbon-intensive cement components with low-carbon alternatives. Calera, a Californian cement manufacturer have developed a process of synthesising cement additives from CO₂ and waste calcium from other supply chains. Untreated flue gas is used as a reagent (rather than pure CO₂) which avoids the expensive process of CO₂ purification. The resulting calcium carbonate product can be used to replace c. 15% of Portland Cement in concrete ([Calera](#)).

Construction Materials and Mine Reclamation

Once demand for industrial waste streams outstrips supply, expansion of mineral carbonation capacity would require the use of mined alkali-rich mineral ores as feedstock. Mineral carbonation has been studied with a number of naturally occurring minerals, and serpentine and olivine (types of ultramafic rock that are rich in magnesium) tend to be preferred due to their performance in test reactions and wide availability ([RSC Review Paper](#), 2014). Basalts and anorthite have also been used in tests and are suitable. These rock types occur in huge quantities at a number of locations, as shown in Figure 2. Availability of rock feedstock is not a limiting factor for mineral carbonation.



Figure 2 - Geographical Distribution of Rock suitable for Mineral Carbonation

It should be noted that relatively large quantities of rock are needed to sequester carbon dioxide. Storing 1 tonne of CO₂ in serpentine via an industrial mineralisation process would typically require 2.1 to 2.5 tonnes, and for olivine it is between 1.8 and 2.8 tonnes ([RSC Review Paper](#), 2014). Markets exist for many of the products of mineral carbonation; iron oxides can be used as feedstock for iron or steel-making processes and carbonates and silicates as aggregates in construction materials. UK manufacturer [Carbon8](#) already produces cost-competitive concrete blocks from carbonate aggregates using the mineral carbonation process. The market for construction aggregates and other bulk products of mineral carbonation is significant (see Table 2) and selling mineral carbonates can offset the costs associated with carbon capture. Large engineering projects for which the carbonate construction materials would be well-suited include tidal lagoons, land reclamation, or flood defences. Furthermore, mineral carbonates could be used for reclamation of abandoned mines, thereby reducing the environmental damage associated with leaching of open pit excavations.

	Global Capacity (Billion Tonnes of Carbon)
Expected Carbon Output over 100 years	2300
Sequestration Options	
Mineral Feedstock for Carbonation	>10,000s – 1,000,000s
Geological Storage Sites	100s – 10,000s
100 Year Market for Carbonates, Silicates and Iron Oxides (from MC)	1240
100 Year Market for Chemicals from MC	<0.1/year
Industrial Wastes for Carbonation	~0.001

Table 2 - Carbon Potential of Storage Options (Sanna et al, 2012)

Small Emitters

Although dependent on supply chain geography, mineral carbonation could be more economically attractive than geological storage for smaller plants (Sanna et al, 2012). This is because geological storage requires access to CO₂ transportation infrastructure from the plant to its final storage location, and therefore the cost per tonne of CO₂ sequestered is largely dependent on access to pipeline infrastructure and overall network and storage capacity. Conversely, mineral carbonation is less reliant on economies of scale, particularly where there is a nearby market for the products. Literature suggests that mineral carbonation is the preferred option for emitters that have annual emissions below 2.5Mt CO₂ (millions of tonnes of carbon dioxide) (Sanna et al, 2012), which currently accounts for 55% of all emissions in the European Emissions Trading Scheme (EU ETS) (see Figure 3).

European CO₂ Emissions by Size of Plant (in terms of emissions)

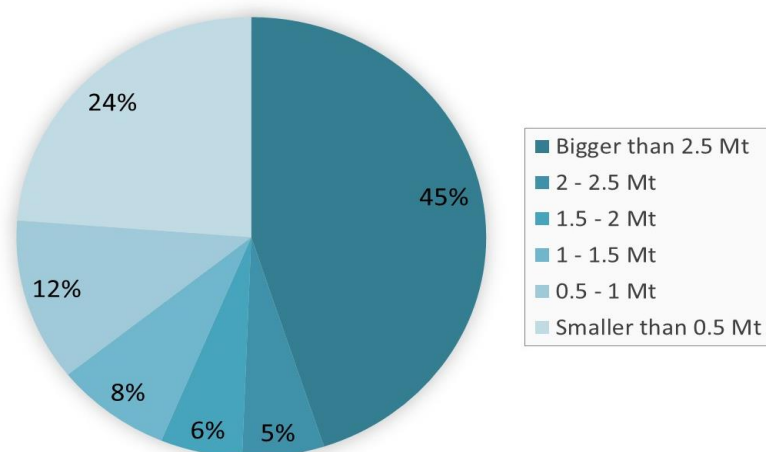


Figure 3 - 2013 EU ETS Emissions Breakdown (analysis by author)

Even if the emissions threshold at which mineral carbonation becomes financially preferable to geological storage is in fact much lower - perhaps at less than 0.5Mt CO₂ emitted annually - this still accounts for nearly a quarter of European carbon dioxide emissions in the EUETS.

Mineralisation technology has been developed to reduce emissions even from small point sources that cannot be dealt with by conventional carbon capture technologies. [Ecospec](#) have trialled an emissions scrubbing system that can be installed on-board container ships, removing SO₂, NO_x as well as CO₂. There is, however, limited information on how Ecospec's CSNO_x technology works (we have yet to see third party literature to support the company's technical claims) and little is known about current state of the system's technological development. It appears that the system is expensive to maintain but can reduce emissions while producing harmless carbonate waste. This type of emissions abatement technology also has uses for a variety of land-based emitters. It is likely that mineralisation-type technologies will have broader utility in reducing emissions for smaller emitters than conventional CCS which may be better suited to groups of large installations.

Policy Challenges

The EU's CCS policy has lagged behind its positive rhetoric on CCS; no recent commercial scale projects have begun operating in Europe and the EU's principal fund for supporting new CCS projects (NER 300) was not allocated to the range of CCS projects first anticipated. Member States have equally made little individual progress although the UK has two commercial scale projects in development pending final investment decisions. Given that the main hurdles in deploying CCS relate to funding, rather than technological barriers, policies should focus on encouraging investment in deep decarbonisation within industrial sectors, where novel processes such as mineralisation could have an important role to play. In our recent report 'Discharging the political storm'⁸ we outlined the actions we believe the EU needs to take to recalibrate its Energy and Climate Package so that it better supports industrial low carbon innovation and deployment.

Sandbag also recently published a briefing on a potential policy tool that would support investment in CCSU, including mineralisation, in industrial sectors: 'Financing deep decarbonisation in industry'.⁹ We believe mineralisation should feature in the EU's definition of CCSU and all future policies at EU and Member State level should treat all CCSU technologies equally, allowing the most suitable solutions to be deployed in the most appropriate locations.

Restrictions on the movement of hazardous wastes in the EU (Waste Framework [Directive](#) 2008/98/EC) permit transportation of small samples of hazardous material across borders. Although these amounts are sufficient for the purpose of lab testing, larger quantities of material are generally required for industrial scale mineralisation performance testing (typically several tonnes). Current licensing rules can act to impede the latter, particularly where a Member State's laws governing the reclassification of hazardous wastes (i.e. changing the status of wastes to enable them to be transported for use as feedstock) are inflexible.

Furthermore, there are few incentives for developers to use of low-carbon building materials and non-extracted construction minerals - such as building aggregate produced via the mineralisation process - which help to mitigate the carbon footprint and environmental impact of construction. New construction materials are only considered acceptable for use in mainstream building works once codes of practice have been updated to certify them, which involves rigorous testing to assess their performance and safety. There are currently many barriers to new low-carbon products entering the market and few or no incentives to use them. This is a concern since CO₂ emissions from cement-making in the EU have risen in recent years, setting the industry on course for emissions levels that are

⁸ Discharging a political storm: Supporting EU competitiveness and innovation in the ETS (Sandbag, July 2015) <https://sandbag.org.uk/reports/discharging-a-political-storm-supporting-eu-competitiveness-and-innovation-in-the-ets/>

⁹ Financing Deep Decarbonisation in Industry (Sandbag, June 2015) <https://sandbag.org.uk/reports/financing-deep-decarbonisation-in-industry/>

several times 2050 targets ([Ecocem, 2013¹⁰](#)). A balance must be struck between enforcing high standards of construction and reducing hurdles that delay best available technology for emissions reductions in becoming available to the market. Relying on the existing approach will result in fewer green innovations being brought to the market and a pace of emissions reductions that will fail to achieve 2050 targets for the cement industry by a wide margin.

Conclusion

No single technology will be the magic bullet that stops climate change. Every technology that can sustainably and cost-effectively reduce or remove greenhouse gases at scale should be considered and supported. The business case for mineral carbonation is feasible for a growing number of value chains, particularly in waste-neutralising and chemical-producing industries. With support for research, effective financial incentives for decarbonisation, standards on the carbon footprint of products and the removal of certain regulatory barriers mineral carbonation could develop into a larger industry with a major role in global decarbonisation strategies.

At a later stage, mineral carbonation may expand beyond industrial waste streams to using mined minerals and could provide an economical route to decarbonisation for a significant proportion of small to medium-sized emitters. This can enable plants where geological storage is uneconomic or impractical to sequester CO₂, expanding the scope of CCS. Wider implementation of mineral carbonation would expand our ability to sequester CO₂ in the medium term, filling in the gaps where geologic CCS is infeasible or uneconomic.

We urge policy makers to adopt an inclusive approach in their definitions of carbon capture and storage and to introduce supportive policies that can help to determine what future role currently novel approaches to CCS can deliver over time.

About this briefing

Full information on Sandbag and our funding is available on our website (www.sandbag.org.uk).

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The logo for Sandbag, featuring the word "sandbag" in a bold, lowercase, blue sans-serif font.

¹⁰ Ecocem (2013) "A Carbon Reduction Roadmap for the Cement and Concrete Sector in Ireland"