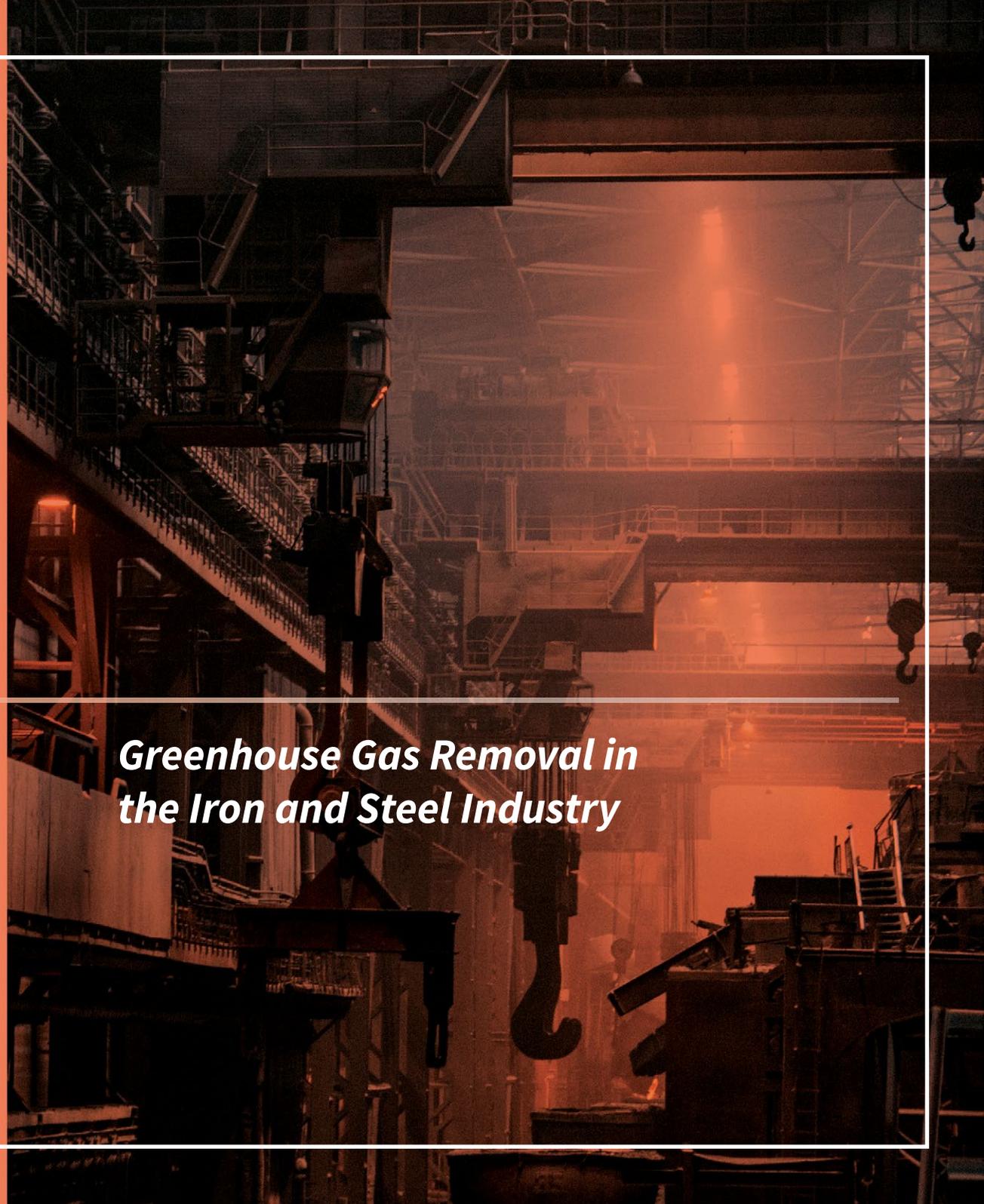


UK GGR Research Programme
Policy Brief

*Greenhouse Gas Removal in
the Iron and Steel Industry*



Summary

The iron and steel industry is responsible for more than 5% of the total greenhouse gas emissions worldwide. It also produces 500 million tonnes of slag as a by-product which has the potential to capture CO₂ by transforming it into stable carbonate minerals. These natural processes can be accelerated by an approach called enhanced weathering which could provide a form of greenhouse gas removal (GGR).

Currently the amount of CO₂ which could be captured by slag is equivalent to only a small proportion of the industry's own emissions, but if there was extensive decarbonisation of the iron and steel industry then this proportion could increase, enabling the industry to become net-zero, or possibly net-negative.

Laboratory-based research indicates that enhanced weathering has good potential for offsetting the iron and steel industry's CO₂ emissions, but uncertainties still exist around the quantities, location and the variability in the chemistry of slag, alongside the environmental impact of this GGR approach.

The 'GGR in the Iron and Steel Industry' project has explored the factors that shape how much carbon could be captured by slag and the uncertainties surrounding the enhanced weathering process.

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Project researchers have estimated that over 190 million tonnes of legacy iron and steel slag are present across the UK. Based upon laboratory data, this could capture up to 57-138 million tonnes of CO₂

Project researchers have estimated that over 190 million tonnes of legacy iron and steel slag are present across the UK. Based upon laboratory data, this could capture up to 57-138 million tonnes of CO₂. In practice, however, there are likely to be challenges to reaching this full potential.

Global volumes of slag and other alkaline materials will change over time, affecting the proportion of industry CO₂ emissions they absorb. The extent of change will rest, to some degree, on policy decisions that shape the sustainability of the global economy and, in turn, the demand for materials. Taking this variation into account, alkaline materials could absorb about 2.9-8.5 gigatonnes of CO₂ per year by 2100 globally. This would make the iron and steel industry (and other producers of alkaline materials) net-zero, or even net-negative in terms of CO₂ emissions, as long as enhanced weathering is combined with deep cuts in carbon emissions in the industry.

The location of slag heaps can represent either a challenge or an opportunity for carbon capture. Not all heaps that make up the 190 million tonnes of legacy iron and steel slag in the UK are suitable for enhanced weathering. This is either because they have high ecological value or because they have been developed for housing. However, the potential for carbon capture at current or recently closed steel-working areas is good. Local or regional governments with a large concentration of slag heaps could integrate them into local carbon management plans. With the right economic incentives for capturing carbon, the heaps could become a valuable source of revenue rather than the environmental liability they represent today.

Recommendations

From a research perspective, considerably more studies and large field-scale trials are needed on carbon capture by slag under real-world conditions. Most of our understanding comes from laboratory studies.

Research also needs to explore the social and environmental implications of removing greenhouse gases through slag. There may be wider trade-offs and limitations, but also co-benefits.

More complete production data and inventories of slag stockpiles should be developed to give a better picture of their carbon storage potential.

From a policy perspective, government needs to ensure appropriate economic incentives for the iron and steel industry to deploy GGR, such as carbon taxes or offset schemes, or carbon cap-

ture integrated into land reclamation schemes. Slag carbonation could ultimately create an important revenue stream that re-shapes the industry's business model and supply chain. Policy makers in this area should consider this possibility in their decisions.

Conducive regulations are needed, for instance, regulatory approval of novel and emerging carbon capture approaches is required. In addition, waste legislation must be in tune with the processes; if not then lengthy administrative procedures and negotiations with regulators could deter industry from recovering slag for new purposes.



1. Introduction

The iron and steel industry has been producing slag as a by-product for hundreds of years. While there is also a long history of slag being re-used as a construction material and as agricultural lime, a large proportion is considered to be waste and typically piled up in heaps. These heaps are an environmental liability for iron and steel producers, as well as local authorities, who must manage the highly alkaline and potentially toxic substances that leach from the slag.

In recent years, there has been growing interest in slag's ability to capture carbon from the atmosphere as part of broader efforts to reach net-zero emissions and prevent further dangerous climate change.

Without intervention, slag captures a very limited amount of atmospheric carbon. However, a new technology known as enhanced weathering (see box 1) could accelerate the carbon capture process to help the iron and steel industry offset its emissions.

The iron and steel industry is currently responsible for more than 5% of the total greenhouse gas emissions worldwide. More than 2 tonnes of CO₂ are released per tonne of steel manufactured, which equates to over 6 tonnes of CO₂ released for every tonne of slag (Renforth, 2019).

Enhanced weathering remains a largely untested technology outside the laboratory and, as with most other negative emission technologies, uncertainty in its potential may limit the rate and extent of its widespread use.

BOX 1 How does slag remove carbon from the atmosphere?

Calcium and magnesium minerals in rocks naturally react with carbon in the atmosphere. These reactions create new minerals – carbonates – which trap the carbon and stop it re-entering the atmosphere. Over long geological time periods, this natural weathering forms carbonate rocks, a process that is part of the rock cycle. Carbonates are able to store carbon for over 100,000 years.

Iron and steel slag, which also contains significant levels of calcium and magnesium minerals, removes carbon from the atmosphere in the same way.

Since the 2000s, researchers have been exploring how to enhance this natural process of creating new minerals and rocks to maximise carbon absorption by slag. If enough calcium or magnesium dissolves during the enhanced weathering process, new carbonate minerals form that, as in nature, trap carbon for tens of thousands of years.

So far, enhanced weathering has mostly been studied in laboratory experiments, but demonstrator projects will be conducting larger-scale experiments under 'real-world' conditions within the next few years.

Exact methods for enhanced weathering still need to be explored in these field-scale studies. In practice, enhanced weathering may simply adapt existing slag management techniques to maximise carbonate and rock creation. For example, slag may be ground up into particles and carefully placed to maximise atmospheric CO₂ exposure, or CO₂ may be pumped into the heaps.

Research conducted by the ‘GGR in the Iron and Steel industry’ project has reduced some of the uncertainties around enhanced weathering. It has estimated how much carbon could be removed from the atmosphere by slag over the next century based on: levels of iron and steel production and drivers of future production, how the slag is managed, the slag’s chemical composition and its location.

The project's findings help improve our understanding of the feasibility of this GGR technology, from technical, economic, social and environmental standpoints.

BOX 2 CO₂ removal by other alkaline materials

Slag is one example of an alkaline material that locks away carbon through weathering. A number of industries produce alkaline materials as waste or by-products that could also potentially remove atmospheric carbon through the same process. These materials include:

- Coal ash
- Biomass ash
- Red mud (a by-product of aluminium production)
- Lime
- Cement kiln dust
- Mine tailings, for example, from gold, diamond and nickel mining

2. Potential estimates of CO₂ removal from slag and other alkaline materials

Levels of CO₂ removal from the atmosphere by slag and other alkaline materials (see box 2) are mainly influenced by management practices, chemical composition, and physical properties e.g. particle size and location.

2.1 Slag management practices

The CO₂ capture from unmanaged slag heaps (i.e. without enhanced weathering) is highly variable, but typically limited to the top few centimetres of the heap. This is because CO₂ cannot access most of the reactive minerals within the slag, either because they are buried beneath the surface or because the slag particles are too large.

Research at disused iron and steel works in the UK provides data on how much carbonation occurs without enhanced weathering. An analysis of samples of slag from legacy heaps in South Wales found that between 0 and 77% of total carbonation potential had been reached across 10 works (out of 48 that operated in the region), (Chukwuma et al., 2021). Based on this, researchers estimated that these 10 heaps had removed between 40 and 608 kilograms of CO₂ per ton of slag and had a capture potential of up to 17 Mt CO₂ by direct carbonation.

A more comprehensive study of samples from a historical slag heap at a disused steelworks at Consett, UK, estimated that around 3% of the maximum carbon-capture potential of the heap may have been realised (Pulkin et al., 2019). This is suggested to be due to limited CO₂ ingress into the material.

Both of these studies demonstrate that, while historical slag does have carbon capture potential, traditional slag management practices will not maximise this potential.

The research identifies several factors to be considered when designing enhanced weathering methods.

Smaller slag particles would provide a greater surface area for the chemical reactions that are needed to form carbonates (see box 1) but there are several trade-offs:

1. Smaller particles may make it more difficult for atmospheric carbon (whether as a gas or dissolved in water) to permeate into the heaps due to compactness and loss of hydraulic conductivity, so reducing the amount of CO₂ that reacts with the slag
2. The crushing of slag into smaller particles will require energy
3. Smaller particles may be more likely to leach alkaline (and potentially toxic) substances which may need to be treated on site so they do not reach the wider environment

In terms of leaching, those particles that are in a good position for carbon capture (i.e., they are well-exposed to CO₂) may also be those that are more likely to leach. Large particles (12-25 mm),

only leach at the surface of a heap and in subsurface regions that can be accessed from the surface by cracks and pores – the same positions that lend themselves well to carbon capture. This means that, without any preventative measures, promoting carbon capture through the positioning or reducing the size of slag particles may result in the leaching of toxic substances. Active management of water in heaps could help operators manage the alkaline leachates.

While the optimal particle size for enabling carbon capture whilst preventing leaching has still not been ascertained, we do have a sense of the size of particles that exist in slag heaps where no enhanced weathering has occurred. For example, around 80% of the material recovered from Consett was over 4 mm in diameter and over 50% was more than 10 mm in diameter. These particle sizes will withhold a large amount of minerals needed for carbonation.

Since CO₂ supply is often the limiting factor in slag carbonation, there is potential for synergy with on-site Direct Air Capture systems, which can supply CO₂. Suitable CO₂ concentrations and CO₂/H₂O ratios need investigation.

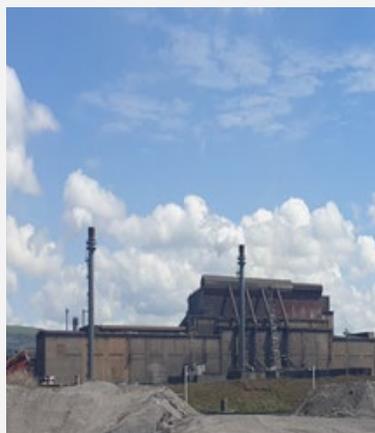
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Exploring the chemistry of historic slag deposits could help understand the long-term constraints on CO₂ sequestration

AT THE SURFACE

'tailored slag' + atmospheric exposure
= good CO₂ SEQUESTRATION



WHEN BURIED

'historic slag' + limited mass transfer
= poor CO₂ SEQUESTRATION



FIGURE 1: Conceptual limitations of CO₂ storage in slag (Pullin et al., 2019).

2.2 Internal chemistry of slag

Slag's internal chemistry influences carbon storage and varies according to the materials used in iron and steel production. The greater the calcium and magnesium content, the greater the carbonation potential. Exploring the chemistry of historic slag deposits could help understand the long-term constraints on CO₂ sequestration.

Iron slag (or 'blast furnace slag') has different properties to steel slag. Analyses of samples from 10 disused works in South Wales revealed that blast furnace slag typically contained 6-62% calcium oxide and 1-11% magnesium oxide (Chukwuma, 2021). Analyses of samples from the disused Consett steelworks estimated that slag contained 34-42% calcium oxide by mass and 8-12% magnesium oxide (Mayes et al, 2018). Analysis of the samples from Consett, estimated that the sequestration potential for the largest heap was 6-11 million tonnes of CO₂ in the absence of enhanced weathering, or 10-19 million tonnes of CO₂ through enhanced weathering. The variation in potential is due to the variation in concentrations of calcium and magnesium.

2.3 Location

While plenty of slag may be available, not all of it can be used for carbon capture due to its location. Carbon capture by slag is a more valuable economic and carbon management prospect in some regions than others (see figure 1).

Research shows that over 190 million tonnes of legacy iron and steel slag are present across current and former iron and steel working regions of the UK, with a theoretical CO₂ capture potential of up to 57-138 million tonnes (Riley et al., 2020).

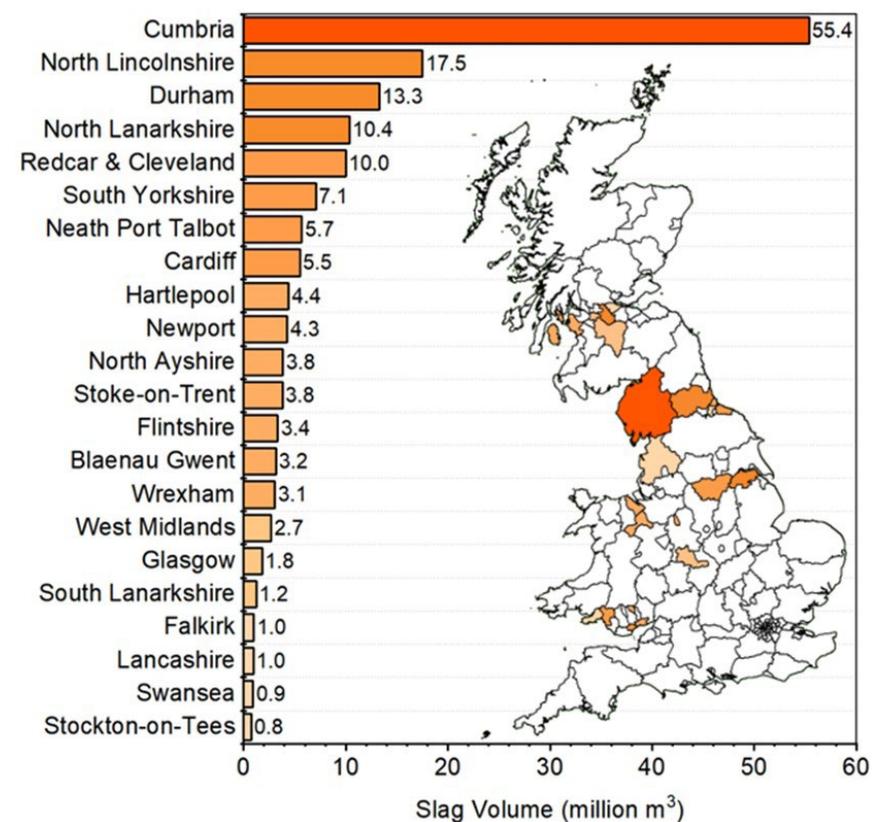
However, a third of these heaps are close to conservation areas and processing the slag may disturb the land considerably. Furthermore, many sites have been redeveloped for housing; nearly 30% are classified as urban cover (Riley et al., 2020). Thus, in practice, a significant proportion of the sites cannot be used for carbon capture. A better understanding of the ecological and social values of historic sites can help steer decisions on whether they should be used for carbon capture or not.

These findings also suggest that slag produced in recent decades may have the greatest potential for carbon capture in that they may be in more accessible locations, which have not yet been repurposed for other land uses.

Slag heaps are concentrated in areas where local geological conditions have enabled steel and iron works to thrive. These tend to be areas that are industrial, and in the UK they are largely found in the north-west and north-east of England, and in central Scotland (see figure 2) (Riley et al., 2020).

This uneven spread could translate into an important opportunity for local authorities with large numbers of historic heaps within their borders to use enhanced weathering as part of carbon management strategies. For example, the emissions for the region of Cumbria are about 7.4 Mt of CO₂ per year, but its large number of slag heaps could cumulatively capture 20 Mt. This potential could, therefore, render the heaps a valuable resource and make the industry in this area net negative.

FIGURE 2: Distribution of slag deposits in the UK (Riley et al., 2020).



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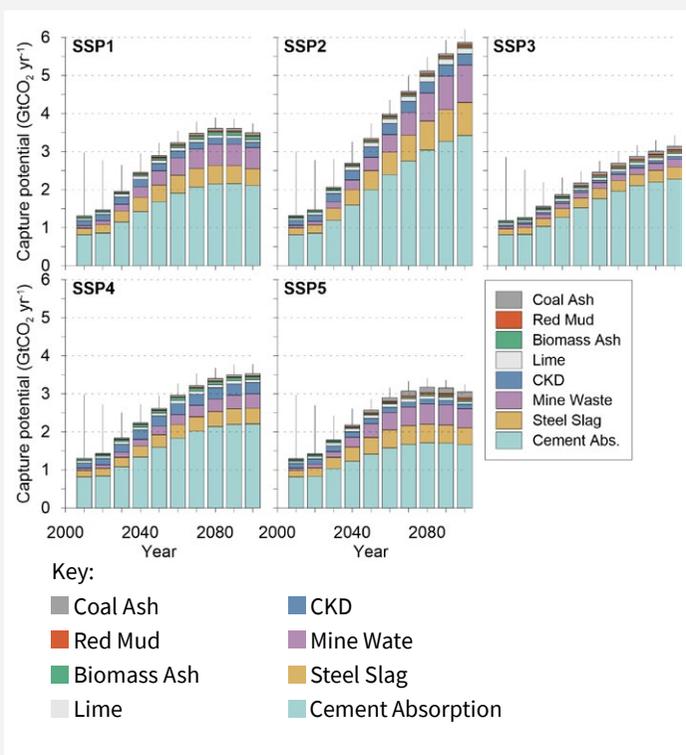


FIGURE 3: Forecast of carbon capture potential of slag and other alkaline material through to 2100 under five SSPs (Renforth 2019).

SSP1: sustainable pathway;

SSP2: ‘business as usual’;

SSP3: high competition between regions, focus on domestic development;

SSP4: high social and economic inequalities;

SSP5: fossil-fuelled development.

3. Can this approach enable the iron and steel industry to become net negative?

Research suggests that enhanced weathering could help the iron and steel industry reach net-zero or net-negative carbon emissions (Renforth, in prep.). This requires extensive cuts in carbon emissions through cleaner energy supply and improvements in energy efficiency, as well as carbon capture and storage (CCS) technologies.

The extent of carbon capture naturally varies according to the quantity of slag. However, because slag and other alkaline materials are of low value, there are typically no accurate figures for their quantities. More complete data and inventories of stockpiles will give a better picture of carbon storage potential. In the meantime, production data – and forecasts of future production – are used to estimate volumes. Presently, an estimated 7 billion tons of alkaline materials are produced each year around the world (Renforth, 2019).

3.1 Decarbonisation

Looking to the future, the total and global GGR potential across a range of alkaline materials, including iron and steel slag, could be about 2.9–8.5 gigatonnes of CO₂ per year by 2100 (see figure 3) (Renforth, 2019). While, in the context of current emissions, 2.9–8.5 gigatonnes of removed CO₂ per year may seem relatively small, the iron and steel industry has plans to decarbonise. With lower future emissions, this figure could make a more significant contribution towards net-negative goals (see figure 4).

The variation in estimates (from 2.9 to 8.5 gigatonnes) is due to differences in future global economic development and its influence on consumption patterns – and therefore the volume of materials produced.

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3.2 Different socioeconomic scenarios

Research has explored estimates of CO₂ removal from enhanced weathering of slag for five socioeconomic scenarios for the future (or ‘Shared Socioeconomic Pathways’ (‘SSPs’) as used in IPCC assessment reports) (Renforth 2019). For example, if society adopts policies that create a resource and energy-intensive global economy (a scenario termed ‘SSP5’) over coming decades, enhanced weathering has the potential to remove 2.9 gigatonnes of CO₂ per year in 2050 and 4.3 gigatonnes in 2100. Under a largely ‘business as usual’ scenario (SSP2), with high material consumption – and so more slag production – removal could go from 3.8 gigatonnes of CO₂ per year in 2050 to 8.5 gigatonnes by 2100.

In comparison to other methods of removing CO₂ from the atmosphere, enhanced weathering of slag has similar capture potential. For instance, afforestation or forest management could sequester 1-1.5 gigatonnes of CO₂ per year, soil carbon management could sequester 3 gigatonnes of CO₂ per year and biomass energy carbon capture and storage (BECCS) could sequester 3.5-5.2 gigatonnes of CO₂ per year (National Academy of Sciences, Engineering, and Medicine, 2018).

3.3 Enabling use of lower grade ores

Enhanced weathering could enable the use of lower grade ores by the iron and steel industry (see figure 4). At present, the iron and steel industry work with high-grade ores that typically have an iron content of around 60-66%. These generate between 0.25 and 0.30 tonnes of slag per tonne of iron produced, and around 0.13 to 0.2 tonnes per tonne of steel. Ores with lower iron content tend to be avoided, partly because they produce more slag (around 1.0 to 1.2 tonnes) which is a liability to the industry. However, with the right economic incentives to capture carbon (see ‘Next Steps’), slag could become a resource, and extra production of this material may benefit the industry financially.

CO₂ capture by slag could also offset the high carbon emissions associated with using low-quality ores which are more energy-intensive to process. For example, for ore with 40% iron content, CO₂ emissions could drop from around 2 tonnes per tonne of steel produced to less than 0.5 tonnes (see figure 4). The potential to recover secondary materials, such as vanadium, from the slag could further enhance slag’s resource value (Riley, et al., 2020).

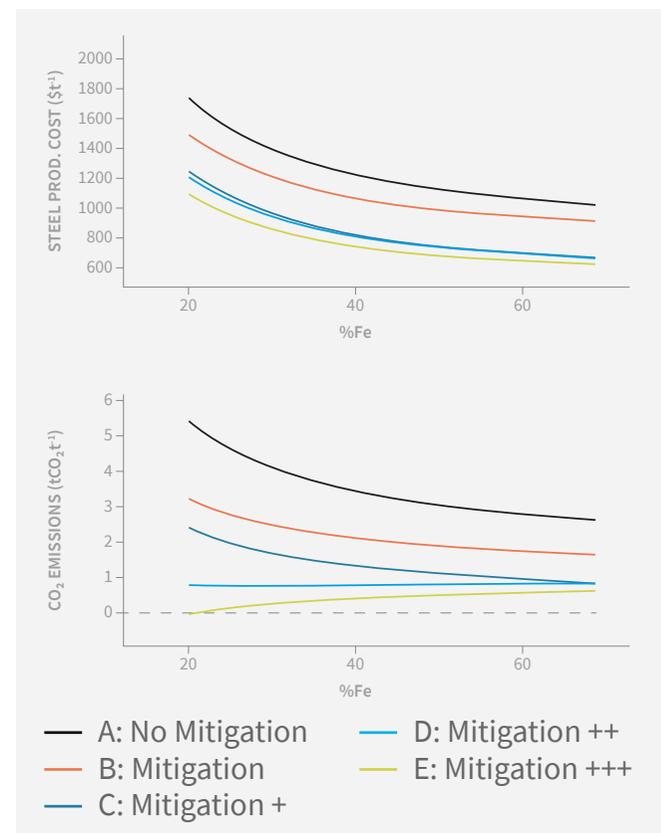


FIGURE 4: Emissions from the steel industry as a consequence of iron ore grade. Red dots indicate current typical levels of iron in ore processed by the steel industry.

With the right economic incentives to capture carbon, slag could become a resource, and extra production of this material may benefit the industry financially

Next steps

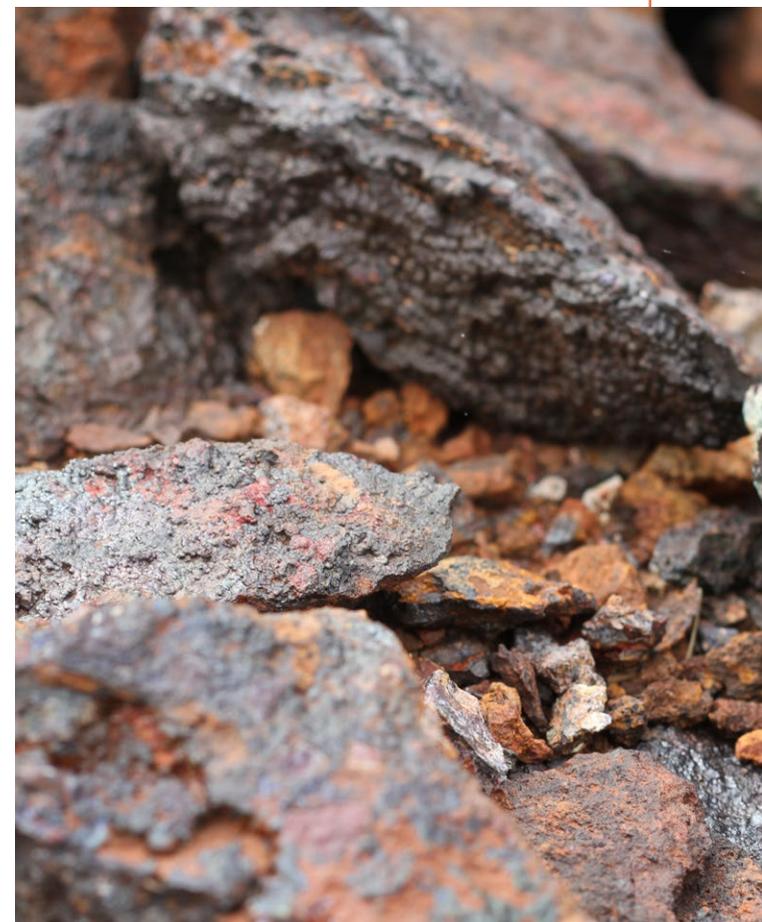
Considerably more research is needed to assess the potential for optimising CO₂ capture at ambient conditions to build upon the laboratory evidence and the initial analyses conducted at historical slag heaps to date. Since CO₂ supply is often the limiting factor in slag carbonation, there is high potential for synergy with on-site Direct Air Capture systems, which can deliver CO₂. In this case, suitable CO₂ concentrations, CO₂/H₂O ratios and delivery mechanisms (e.g., fluid circulation), need investigation.

The iron and steel industry need the right economic incentives to capture carbon using slag, such as a carbon tax or removal/offset markets. This could also alter the industry's business model. For example, at US\$100 per ton of CO₂, the 17-25 megatons of CO₂ capture potential of South Wales's slag heaps could be worth US\$2-3 billion (Chukwuma, 2021).

A supportive regulatory environment is also required. Government intervention is needed to ensure regulatory approval of novel and emerging carbon capture approaches. Regula-

tory disincentives to capture carbon with slag should also be removed, for example by making waste legislation more flexible. At present in the UK and the EU, for instance, the bulk re-using of slag breaks the terms of operators' environmental permits to manage slag heaps and prevent pollution. The lengthy process involved in both securing the permit and negotiating with regulators to adjust the terms may deter iron and steel firms from using the slag in innovative ways.

Furthermore, the broader environmental and social consequences of slag-based GGR must be explored before it is deployed at scale. For instance, ash and slag may have other positive environmental uses as replacement lime, for example in cement production. The properties of different alkaline materials and production sites will need unique and ongoing assessments to provide a better picture of the environmental implications of enhanced weathering.



Government intervention is needed to ensure regulatory approval of novel and emerging carbon capture approaches

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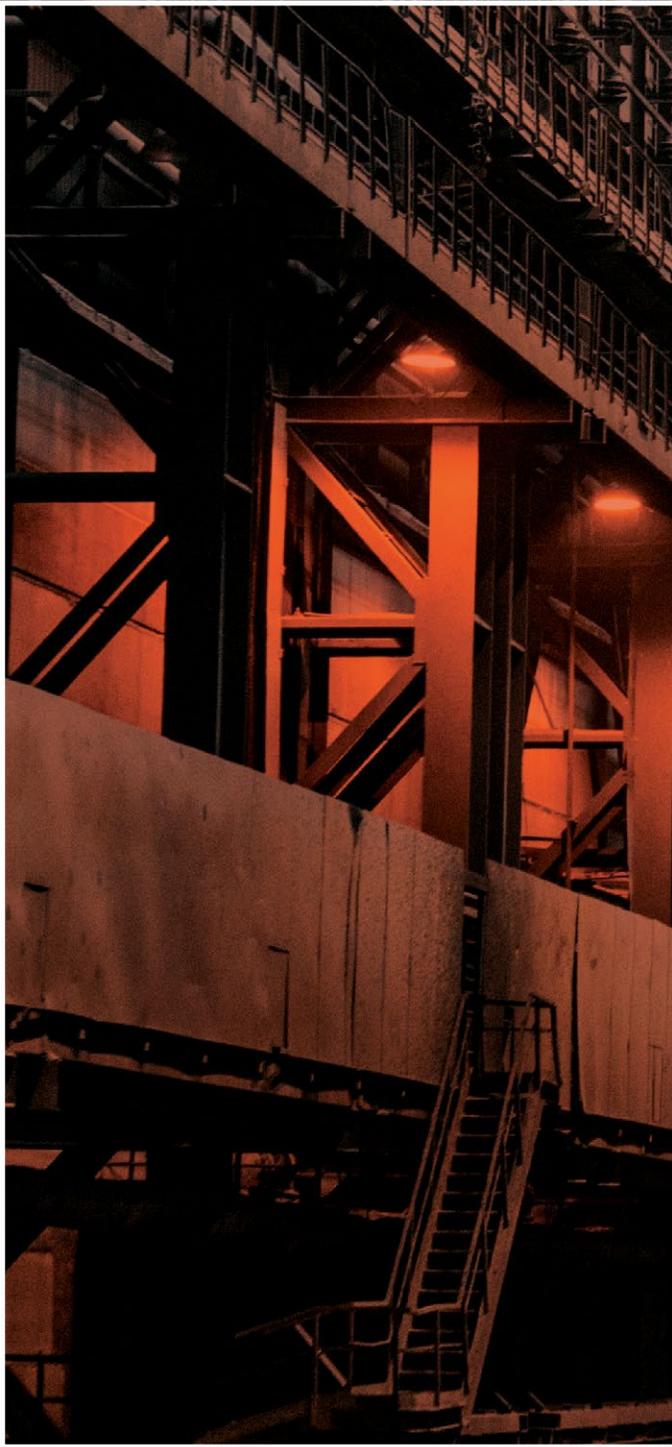
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About the programme

The Greenhouse Gas Removal research programme aims to improve our knowledge of the options for removing carbon dioxide and other greenhouse gases from the atmosphere. Through eleven component research projects it addresses the environmental, technical, economic, governance and wider societal aspects of such approaches on a national level and in an international context to inform implementation of climate policy pathways that include large scale removal of carbon dioxide.

Feasibility of Afforestation and Biomass Energy with Carbon Capture and Storage for Greenhouse Gas Removal (FAB-GGR) is one of eleven components. This policy brief was created in collaboration with Dr Phil Renforth and Dr James Campbell.

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