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The Climate Company

Carbon accounting of recarbonation in lime products

Main considerations for compliance and voluntary carbon markets

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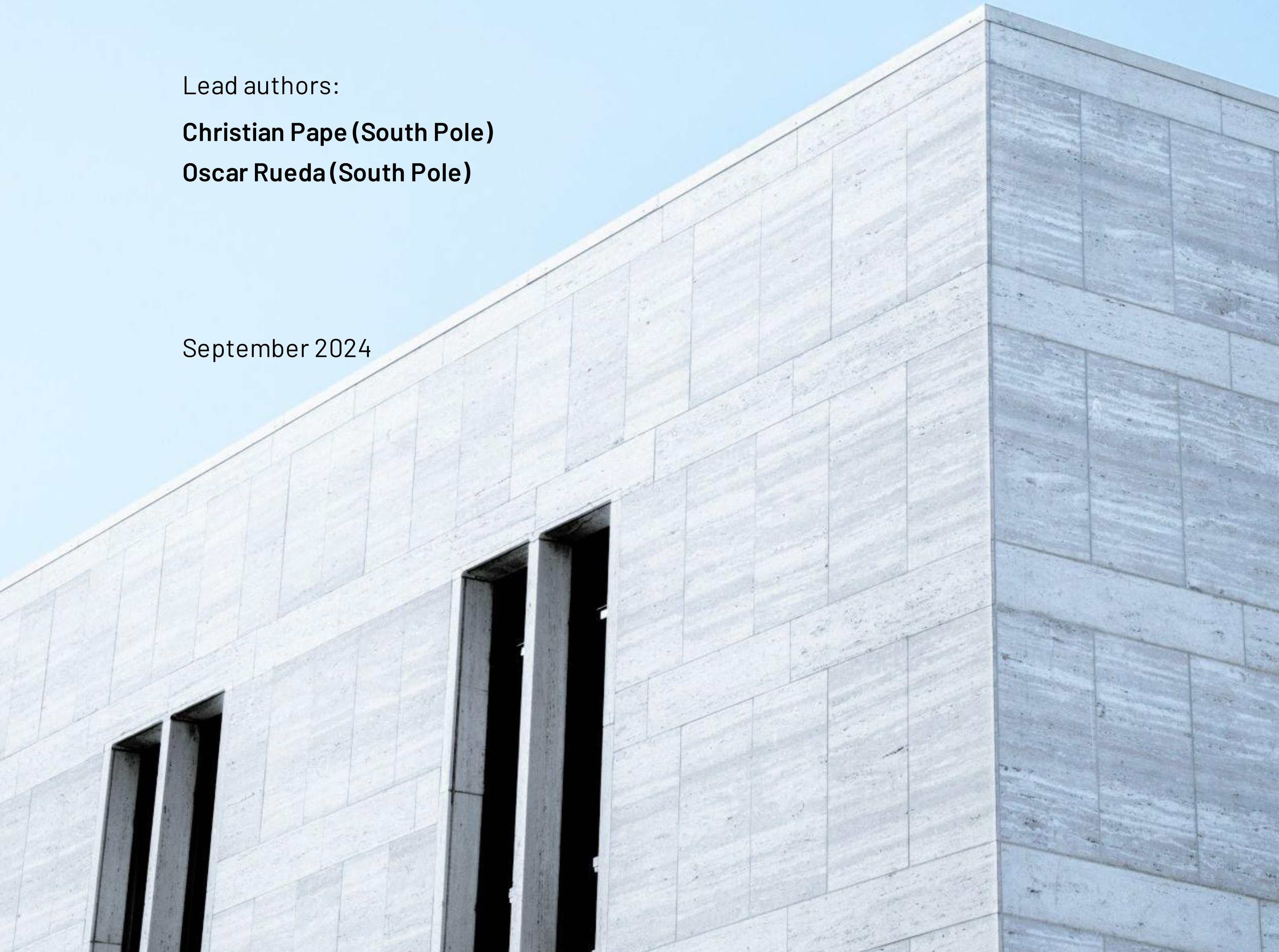

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Disclaimer

Sponsored by EuLA, South Pole's technical carbon markets experts developed this report in collaboration with EuLA's lime industry experts.

This report was developed by South Pole's technical carbon markets experts in collaboration with industry experts from EuLA. Such a collaboration seeks to reflect the perspectives of both the lime industry and carbon markets professionals. However, the views expressed in this report may not necessarily represent the positions of every EuLA member or South Pole on all topics discussed.

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List of abbreviations

APCR	Air Pollution Control Residues
BECCS	Bioenergy with carbon capture and storage
$CaCO_3$	Calcium carbonate; limestone
CaO	Calcium oxide; lime; quicklime
$Ca(OH)_2$	Calcium hydroxide; slaked lime; hydrated lime
CCS	Carbon capture and storage
CCUS	Carbon capture, utilisation and storage
CDR	Carbon dioxide removal
CO_2	Carbon dioxide
CRCF	Carbon Removals and Carbon Farming
CSH	Calcium silicate hydrate
DACCS	Direct air carbon capture and storage
EuLA	European Lime Association
EU	European Union
GHG	Greenhouse gas
ICROA	International Carbon Reduction and Offset Alliance
MRV	Monitoring, reporting and verification
PA	Paris Agreement
PCC	Precipitated Calcium Carbonate
QM	Quantification Measure
SO_2	Sulphur dioxide
SLB	Sand lime bricks
VCM	Voluntary carbon market

Executive summary

This document examines the quantification of carbon dioxide (CO_2) sequestration by lime products[1] after their production phase within carbon markets. Herein, this process is referred to as "recarbonation" to illustrate that lime products reabsorb some of the CO_2 that was initially emitted during their production.

Recarbonation is a key process in the lime cycle, where lime products can absorb CO_2 from the atmosphere and be converted back into calcium carbonate. Through recarbonation, lime products can absorb significant proportions of CO_2 released during lime production from the atmosphere and on average - in the first year, more than a third of the initially generated lime process emissions. This absorption rate varies based on factors such as the exposure conditions and duration. Global estimated uptake of CO_2 by lime increased from 33.62 Mt CO_2 per year in 1930 to 127.86 Mt CO_2 per year in 2020, with a cumulative carbon sequestration of approximately 5.30 Gt CO_2 between 1930 and 2020, equivalent to 38.83% of the process emissions during the same period.[2]

The analysis by South Pole, in collaboration with the European Lime Association (EuLA), considers three perspectives:

- Scientific perspective: It summarises scientific evidence on recarbonation in selected lime products.
- Carbon markets perspective: It explains current challenges in the accounting of recarbonation within compliance and voluntary markets.
- Policy and standards perspective: It presents a set of quantification measures and key considerations for policymakers and carbon-markets standard setters to enhance the quantification of lime products' life-cycle emissions.

Sponsored by EuLA, South Pole's technical carbon markets experts developed this report in collaboration with EuLA's lime industry experts. The aim is to support policymakers, particularly in the European Union (EU) and standard setters to enable the quantification of lime products' life-cycle emissions within compliance and voluntary carbon markets. EuLA envisions a carbon-negative sector by 2050, which aligns with the European Green Deal and its legally binding target to achieve climate neutrality by around 2050. The lime industry plays an essential role for many sectors in the EU and beyond, thanks to its versatility for everyday products and use in a wide range of processes. For example, it is a critical component in the production of iron, steel, glass, building materials, pulp and paper, as well as in the protection of the environment from gaseous and liquid polluting processes and treatments. It is also a key farming product in animal care, animal feed and human food chains and also a critical part of potable water treatment for human consumption and the treatment of sewage sludges, including protection of human life from diseases. Key infrastructure projects including rail, airfields, highways and canals rely on lime treatment of soils to provide efficient alteration of in situ materials to be incorporated in the temporary and permanent works.

[1] For the sake of simplicity and readability, the term lime products is used to refer to any materials related to the processes of recapturing of CO_2 by lime. This includes products, co-products and possibility wastes that are obtained from manufacturing processes where lime is used.
[2] Bing et al. (2023), 'An investigation of the global uptake of CO_2 by lime from 1930 to 2020', Earth Syst. Sci. Data, 15, 2431–2444, https://doi.org/10.5194/essd-15-2431-2023. Amounts of CO_2 sequestered shown have been recalculated as the paper deals with lime sequestration in pure carbon.

The lime industry faces a major climate mitigation challenge due to the substantial and unavoidable emissions during lime production. Nevertheless, it holds the potential to become carbon-negative in the long term. That is, it could become a net sink of emissions from the atmosphere rather than a net source of emissions into the atmosphere. Net negative emissions could be possible if the lime production emissions are eliminated and the lime products continue to absorb more CO_2 through recarbonation or enhanced recarbonation. Eliminating most of the emissions from lime production is possible by both supplying the required energy from renewable sources and by capturing and permanently[3] storing process emissions from lime production (e.g., by using carbon capture and storage (CCS) technology).

Carbon markets can play a central role in realising lime's full climate mitigation potential. A robust carbon accounting of lime's emissions is a prerequisite for achieving emission reductions in the short term and enabling removals in the long term. Currently, carbon accounting standards and policies account for the emissions resulting from lime production; however, they ignore the re-absorption of CO_2 (i.e., recarbonation) from lime products' use and end-of-life phases. As a result, the quantification of the greenhouse gas (GHG) emissions of lime products is incomplete. Such an incomplete quantification of the life-cycle emissions of lime may hinder potential emission reductions in industry. For example, if lime products' emissions are consistently overestimated within compliance or voluntary markets, this may lead to incentives to replace lime products with other alternatives that may seem more beneficial for the climate. The incomplete quantification also fails to incentivise emission removals, which could be achieved through the adoption of enhanced recarbonation activities and more broadly, the possibility of transforming an industry from a source to a net sink of emissions.

This report presents the carbon accounting challenges to quantify recarbonation in a few selected products:

- Slags from iron and steel production: Iron and steel slags contain alkaline materials, such as CaO, which hydrates to $Ca(OH)_2$ and reacts with CO_2, forming calcium carbonate.
- Sand lime bricks: Building materials that absorb CO_2 through recarbonation during their use phase and end-of-life.
- Absorbents and their residues from flue gas treatment: While a lime-derived absorbent is used to bind acid gases, instantly reducing the facility's CO_2 emissions, their residues hold the potential to further remove CO_2.

The cases illustrate the total CO_2 emissions along the product's life-cycle, the limitations regarding the quantification of recarbonation and potential solutions for a more complete carbon accounting of the entire life-cycle of lime products. Although the number of cases is limited, they were selected to illustrate challenges in industrial processes that may be similar across other cases not explicitly covered. The alternative quantification measures and key considerations focus on implementation within voluntary and compliance carbon markets, with a particular focus on the European policy and

[3] For carbonated materials, the IPCC concludes that the CO_2 stored through mineral recarbonation is virtually certain to be 100% retained after 1000 years, reducing the need for monitoring disposal sites. IPCC (2005). IPCC Special Report on Carbon Dioxide Capture and Storage. Ed. by B. Metz, O. Davidson, H. C. de Coninck, et al. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. https : / / www . ipcc . ch / site / assets /uploads/2018/03/srccs_chapter7-1.pdf.

regulatory framework. Nevertheless, the quantification measures and key considerations may also apply to other jurisdictions globally.

The alternative quantification measures presented include the use of conservative emission factors or monitoring, reporting and verification (MRV) approaches to quantify recarbonation. The quantification measures and key considerations seek to foster a more accurate and comprehensive carbon accounting system, provide a baseline for enhanced recarbonation, incentivise further investment in enhanced recarbonation by the lime industry and ensure that its contributions to climate change mitigation are appropriately recognised within the EU and other jurisdictions. Engaging with regulators to discuss these options could pave the way for more effective climate policies by considering recabonation's climate impact and increased climate ambition by fostering enhanced recarbonation and sector-wide negative emissions.

How to use this report

The report is intended for public use. It aims to support standard setters, EU regulators and policy-makers in more holistically quantifying lime product emissions. However, regulators from jurisdictions outside the EU may also benefit from the proposed alternative quantification measures and key considerations for robust and more complete quantification of lime products' emissions.

Given the broad application of lime products, industry leaders across sectors and the general public may also benefit from the analysis presented in this report. Hence, this report can also support civil society efforts to advocate for the changes needed to incentivise and properly quantify climate mitigation in industry.

1. Recarbonation in lime products

The lime industry currently faces a major climate mitigation challenge due to the substantial and unavoidable emissions that occur during lime production. Nevertheless, it holds the potential to become carbon-negative in the long term. That is, it could become a net sink of emissions from the atmosphere rather than a source of emissions into the atmosphere.

It is well known that lime production releases substantial CO_2 emissions to the atmosphere due to energy use and process emissions. What is less known is that, after the production phase, lime products reabsorb CO_2 from the atmosphere. The amount of CO_2 reabsorption can be equivalent to a substantial fraction of the process emissions (more than one-third, on average in the first year).[4] Net negative emissions could even be possible if the CO_2 reabsorption during lime products' use phase and end-of-life outweighs the production emissions. Virtually eliminating production emissions could be possible by using low-carbon energy sources and capturing and permanently storing the process emissions (e.g., through carbon capture and storage technologies with storage in geological formations or durable products) rather than simply emitting them into the atmosphere.

This section contextualises recarbonation's carbon absorption within lime products' life-cycle emissions. It presents three illustrative examples from selected lime applications and briefly introduces the potential to achieve negative emissions.

1.1. The lime industry in context

The lime industry plays a key role in several sectors and lime remains largely irreplaceable due to its unique chemical properties. It is vital in many applications and sectors, including iron and steel production, construction and environmental management as a sorbent for flue gas cleaning and precipitant for effluent treatment.

In the iron and steel industry, lime acts as a flux to remove impurities such as silica, phosphorus and sulphur from iron ore during the smelting process. This ensures the production of high-quality steel by promoting the formation of slag that can be easily removed. Without lime, the efficiency and quality of steel production would be severely compromised.

The construction sector relies heavily on lime-based products such as building blocks, mortar, render and plaster, which are fundamental to building construction. Lime often enhances durability, strength and workability of building materials, increasing the resilience of buildings by improving their resistance to weathering and decay.

Key civil engineering infrastructure projects including rail, airfields, highways and canals rely on lime treatment of soils to provide efficient alteration of in situ materials to be incorporated in the temporary and permanent works.

Power plants and industrial plant flue gas cleaning systems use lime-based products to remove harmful pollutants, such as sulphur dioxide (SO_2) and other acid gases, before they are released into

[4] Grosso et al. (2020). 'Literature review on the assessment of the carbonation potential of lime in different markets and beyond', Assessment on Waste and Resources (AWARE) Research Group, Politecnico di Milano (PoliMI), https://eula.eu/wp-content/uploads/2023/11/LITERATURE-REVIEW-ON-THE-ASSESSMENT-OF-THE-CARBONATION-POTENTIAL-OF-LIME-IN-DIFFERENT-MARKETS-AND-BEYOND.pdf

the atmosphere. Lime-based products are effective in capturing these pollutants, contributing to cleaner air and environmental compliance.

Lime is also a key farming product in animal care, animal feed and human food chains and also a critical part of potable water treatment for human consumption and the treatment of sewage sludges, including protection of human life from diseases.

1.2. Lime production and the lime cycle

Lime production begins with the extraction and processing of limestone, which is heated to produce lime, which causes the release of CO_2. During the usage and end-of-life phases, lime products reabsorb CO_2 from the atmosphere, significantly offsetting some of the emissions released during production (Figure 1).

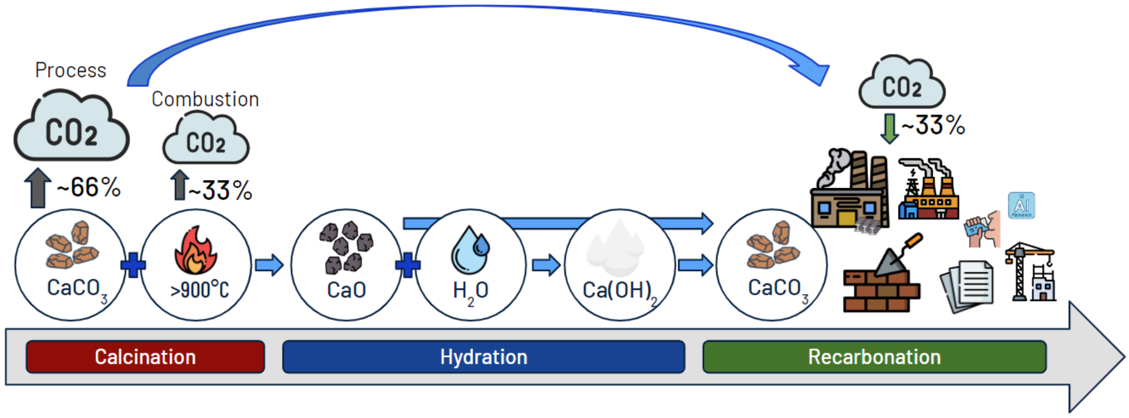

Figure 1: Lime cycle. The lime cycle is a chemical process in which limestone (calcium carbonate, $CaCO_3$) is heated to produce quicklime (calcium oxide, CaO), the main product of the lime industry and carbon dioxide (CO_2) is released. Lime reacts with water to form hydrated lime (calcium hydroxide, $Ca(OH)_2$). When hydrated lime is used in a variety of applications, CO_2 from the atmosphere reacts with the available hydrated lime, which is recarbonated to form limestone, completing the cycle. When quicklime is used directly in many applications, it commonly undergoes hydration and forms hydrated lime, which can then react with carbon dioxide from the atmosphere to become limestone. The ~33% of CO_2 which is reabsorbed from the atmosphere (right) corresponds to the process emissions (~66%, left) during the lime production and is reabsorbed during the first year of their use.[5]

Calcination

After the extraction of limestone ($CaCO_3$), the lime cycle begins with the calcination of the limestone. This process starts with heating crushed limestone in a kiln at high temperatures, typically between 900 and 1000 degrees Celsius. During calcination, limestone decomposes into lime, also referred to as quicklime (CaO) and releases CO_2. These process emissions typically make up more than two-thirds of the total emissions caused by the production of lime. Less than one-third of the total CO_2 emissions come from the combustion of fossil fuels (or a mix of fossil and biogenic fuels) needed to achieve the necessary high temperatures and are not part of the lime cycle and will therefore not be the focus of the discussion in this paper.

Hydration

After calcination, the lime produced can be further processed by mixing it with water. This reaction produces hydrated lime or calcium hydroxide ($Ca(OH)_2$). Due to its reactive properties, hydrated lime

[5] Icons used throughout this report, in all figures, were made by Freepik from flaticon.com.

is used in various applications, as discussed previously. If lime (CaO) is directly used, the hydration transformation to $Ca(OH)_2$ can happen during the application. As the overall lime cycle remains fundamentally the same regardless of whether quicklime or calcium hydroxide is used, both forms are referred to collectively as 'lime' for simplicity where appropriate in this report.

Recarbonation
Over the course of its use phase or at the end of its life, lime products will capture CO_2 from the atmosphere. This process converts lime back into its stable form, calcium carbonate.

1.2.1. Recarbonation

Recarbonation is a key process in the lime cycle, where lime products can absorb CO_2 from the atmosphere and be converted back into calcium carbonate.

Through recarbonation, lime products can absorb significant proportions of CO_2 released during lime production from the atmosphere and on average - in the first year, more than a third of the initially generated lime-containing emissions. This absorption rate varies based on factors such as the exposure conditions and duration. Global estimated uptake of CO_2 by lime increased from 33.62 Mt CO_2 per year in 1930 to 127.86 Mt CO_2 per year in 2020, with a cumulative carbon sequestration of approximately 5.30 Gt CO_2 between 1930 and 2020, equivalent to 38.83% of the process emissions during the same period.[4]

The global potential of recarbonation is substantial, given the extensive use of lime in various industries. However, the process and carbon sequestration lime-containing potential of recarbonation does not exclusively apply to lime and lime-derived products, by-products and wastes. The annual global potential for CO_2 uptake through lime and similar behaving alkaline materials could range from 2.9 to 8.5 Gt of CO_2 per year by 2100.[6] This highlights the crucial role that recarbonation and enhanced recarbonation could play in mitigating industrial CO_2 emissions on a global scale.

Recarbonation and enhanced recarbonation

Recarbonation of lime happens in various stages and at largely varying rates. The main drivers include the surface area of the lime-containing material, the environmental conditions (such as the ambient humidity and temperature) and the exposure duration to atmospheric CO_2. For instance, lime-stabilised soils in agriculture and lime mortar used in building constructions have been identified as significant contributors to carbon sequestration due to their widespread use and exposure to atmospheric CO_2 over time. Lime-stabilised soils captured 51.23 Mt CO_2 in the year 2020 and 2.31 Gt of CO_2 cumulative from 1930 to 2020.[2] Moreover, the continuous improvement in the understanding of recarbonation processes and the development of new technologies for enhancing CO_2 uptake efficiency is likely to increase the relevance and impact of recarbonation. For example, optimising exposure conditions and using lime-based materials in atmospheric CO_2 capture technologies can significantly enhance the carbon sequestration potential of the unreacted lime present in lime products.

[6] Renforth, P. (2019), 'The negative emission potential of alkaline materials', Nat. Commun., 10, 1-8, https://doi.org/10.1038/s41467-019-09475-5.

While recarbonation has been mentioned so far as the chemical process in which CO_2 reacts with lime to form calcium carbonate, the following two processes (also shown in Figure 2) will be distinguished due to their significance in the carbon accounting approaches that will be discussed in later sections:

1. Recarbonation: Current processes where CO_2 that is present in the atmosphere is absorbed by lime, becoming chemically bound and which takes place in the absence of additional efforts to increase the amount of CO_2 absorbed through such processes.
2. Enhanced recarbonation: Processes through which the amount of CO_2 that is absorbed from the atmosphere and becomes chemically bound in the lime-containing product, is increased by additional efforts, such as increasing the exposure of the lime-containing material to the atmosphere.

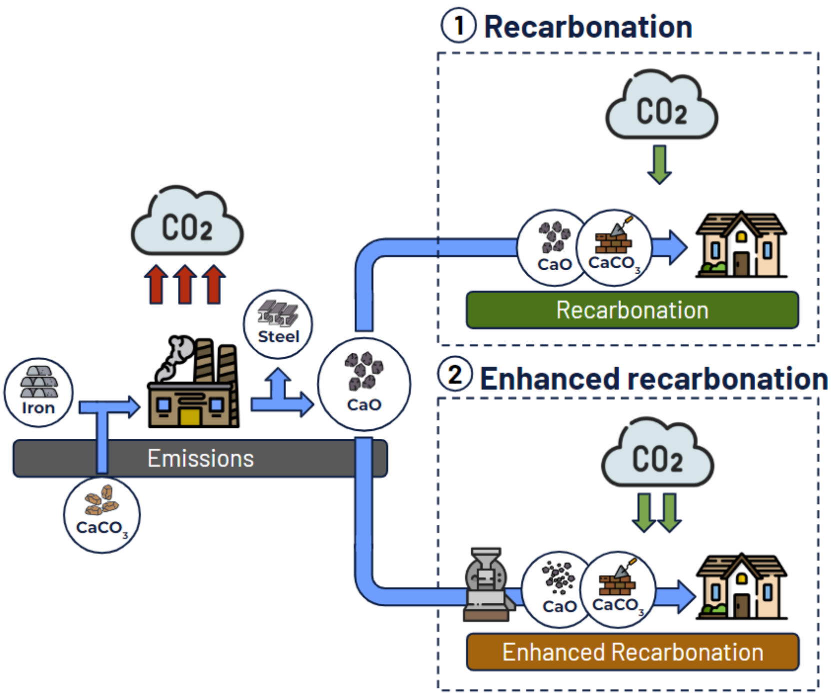

Figure 2: Recarbonation and enhanced recarbonation. 1. Recarbonation: The steel slags (containing unreacted lime) a by-product of steel production are used in building materials and the recarbonated CO_2 is permanently stored. No additional steps to increase the amount of CO_2 in the final building materials are taken. 2. Enhanced recarbonation: Steel slags are used in building materials, but as an additional step compared to the recarbonation, the steel slags are crushed to increase their surface area, thereby increasing the area that can react with the atmosphere, resulting in increased carbon sequestration.

1.3. Lime recarbonation in selected cases

To illustrate the key considerations for quantifying recarbonation in carbon markets with real cases, this section briefly presents three selected cases from the wide range of applications for products from the lime industry and focuses on the first two of the larger markets of the sector:

1. Slags from iron and steel production: Iron and steel slags contain alkaline materials, such as quicklime, which, when exposed to the atmosphere, reacts with water and then with atmospheric CO_2, forming calcium carbonate.

2. Absorbents and their residues from flue gas treatment: While a lime-derived absorbent is used to bind acid gases, instantly reducing the facility's CO_2 emissions, their residues hold the potential to remove CO_2 further when exposed to the atmosphere.
3. Sand lime bricks (SLB): Building materials that absorb CO_2 through recarbonation during their use phase and end-of-life.

The first two cases were chosen due to their large emissions (compared to other cases shown in Figure 3)and their significant carbon sequestration through recarbonation and, potentially, through enhanced recarbonation. All recarbonation or enhanced recarbonation rates refer to the CO_2 emitted during the production of lime, excluding the combustion emissions; according to the Best Available Techniques Reference Document (BREF) for the Cement, Lime and Magnesium Oxide Manufacturing Industries, 786 kg CO_2/tonne of lime is emitted (excluding CO_2 from fuel combustion).

Large potentials in two lime products

The potentials shown in this report are based on a previous literature review, which examined the recarbonation rates of lime for various applications. The review study identified two dominant sectors where lime plays a critical role and holds significant potential for CO_2 absorption: the iron and steel industry and flue gas cleaning systems. In Europe, these sectors could theoretically reabsorb 2,196 kt CO_2 through enhanced recarbonation efforts—1,832 kt CO_2 in the iron and steel industry and 0,364 kt CO_2 through flue gas treatment.[7] These enhanced recarbonation potentials are based on lime consumption in Europe in 2018 and are expected to be sequestered within the first five years.[4] This potential excludes the recarbonation that happens without intervention and highlights the difference between the current maximum recarbonation potential and the maximum enhanced recarbonation potential achievable through activities that increase CO_2 uptake.

In the iron and steel industry, recarbonation occurs through slags left behind after steel and iron production and are commonly used as clinker substitutes for manufacturing blended cements. In flue gas treatment, residues known as Air Pollution Control Residues (APCRs) can be repurposed in construction materials. Since both value chains result in permanent products, the likelihood of re-emitting the CO_2 is low, making these processes a sustainable and long-term carbon sequestration solution.

[7] These values, along with all figures presented in this report, have been adjusted to accurately reflect the true impact of enhanced recarbonation efforts. In the literature review (Grosso et al., 2020, footnote 4), the maximum enhanced recarbonation values represent the upper limit of CO_2 sequestration for a given product and include standard recarbonation quantities within these maximum possible values.

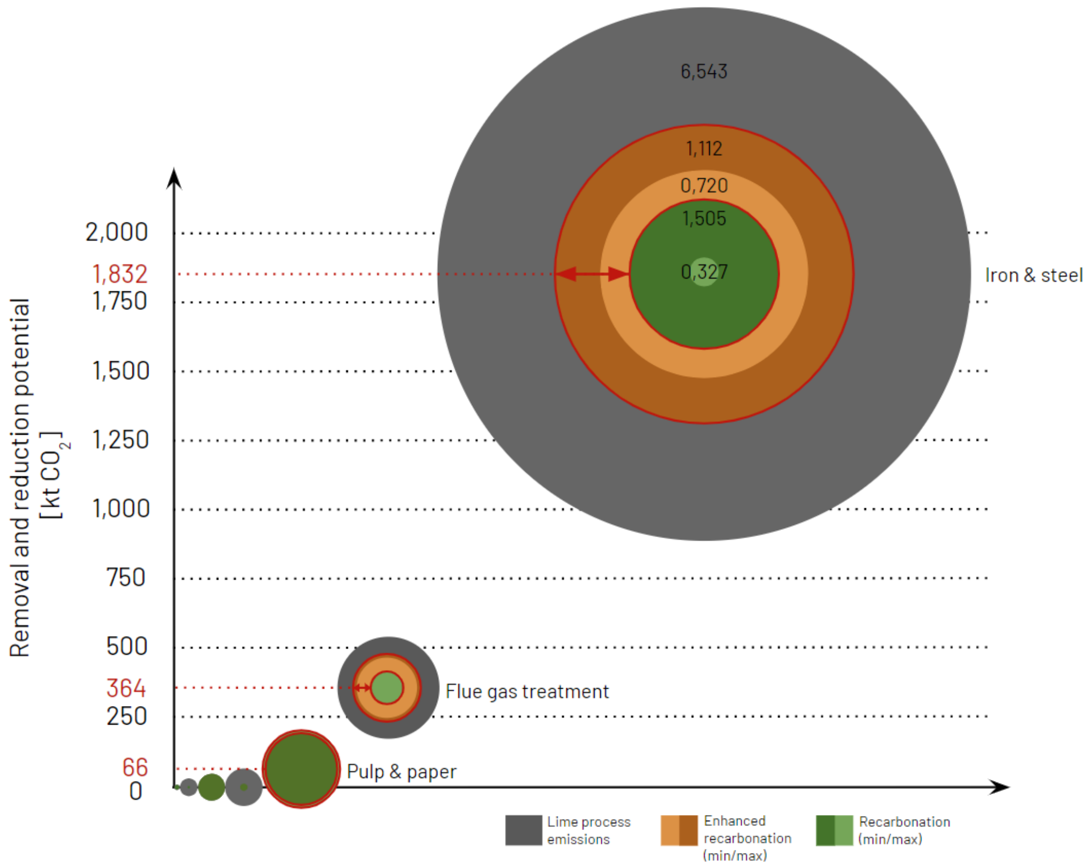

Figure 3: Reduction and removal potential of industries using lime for their applications, based on the lime consumption in Europe in 2018.[4] The potential shown (red numbers on the y-axis) for each sector, is the delta between the maximum recarbonation potential that occurs today and the maximum enhanced recarbonation potential that could be achieved with activities that increase CO_2 uptake. The sectors are lined up along the y-axis according to their reduction and removal potentials. From left to right: Pure air lime mortars, aluminium production, drinking water treatment, mixed air lime mortars, pulp and paper, flue gas treatment and iron and steel industry.

1.3.1. Iron and steel industry

In the iron and steel industry, lime is added to improve the quality of iron and steel by removing impurities. In 2018 alone, the iron and steel industry in Europe used 8.325 Mt of lime for these refining processes.[4] In addition to iron and steel, slag is also used as a valuable resource in the construction industry, for example, as a component in cement and concrete, road construction and soil stabilisation.

Iron slag

Iron slag is a by-product of the blast furnace process used to produce iron. When iron ore is heated with coke and limestone in a blast furnace, molten iron and slag are produced. This slag is rich in calcium, magnesium, aluminium and silicon oxides. Because of its high lime content, iron slag is widely used in the construction industry. Specifically, 81% of iron slag is used as a component in cement and concrete and 21% is used for road construction.[8] This use significantly increases the strength and durability of these applications.

Steel slag

Steel slag is produced during the steelmaking process. Steel slag has a lime content than iron slag, making it more effective for carbon sequestration through recarbonation processes. Approximately 77% of steel slag is used in road construction, soil stabilisation and as a raw material in cement production.[8] Its high reactivity and calcium content make it ideal for these applications as well as for carbon sequestration.

Carbon sequestration potential

These CO_2 uptake amounts and potentials (Figure 4) are divided into the amounts currently absorbed by the slags through recarbonation and the theoretical potentials that could be achieved through increased recarbonation efforts.

Recarbonation: For iron slag, the CO_2 uptake is negligible over long periods, with field studies showing limited recarbonation even after 100 years. In contrast, steel slag can achieve approximately 5% CO_2 uptake in four months, increasing to up to 28% over one year.

Enhanced recarbonation: For iron slag, direct recarbonation can result in up to 7% CO_2 uptake, while indirect routes can achieve up to 31% CO_2 uptake. For steel slag, enhanced recarbonation processes can increase the CO_2 uptake from the atmosphere to between 39% and 56% CO_2.

Techniques for enhanced recarbonation

Direct recarbonation: Involves the exposure of slag to CO_2 under controlled conditions, often at elevated temperatures and pressures to accelerate the reaction. This method offers higher rates of carbon sequestration compared to recarbonation happening today and is suitable for industrial-scale applications. However, it requires specialised equipment and energy inputs to maintain the necessary conditions.

Indirect recarbonation: Involves extracting reactive components from the slag, which are then recarbonated in a separate step. This method can achieve higher overall CO_2 uptake and allows for better control over the recarbonation process. However, it is more complex and involves additional processing steps, which may increase costs and energy consumption.

Accelerated weathering: Enhances the natural weathering process of slag by optimising environmental conditions such as moisture, temperature and CO_2 concentration. This method is relatively low-cost and has the potential for large-scale application. However, the rate of recarbonation can still be slower compared to direct and indirect methods.

[8] Euroslag, (2016). Statistics. https://www.euroslag.com/products/statistics/statistics-2016/

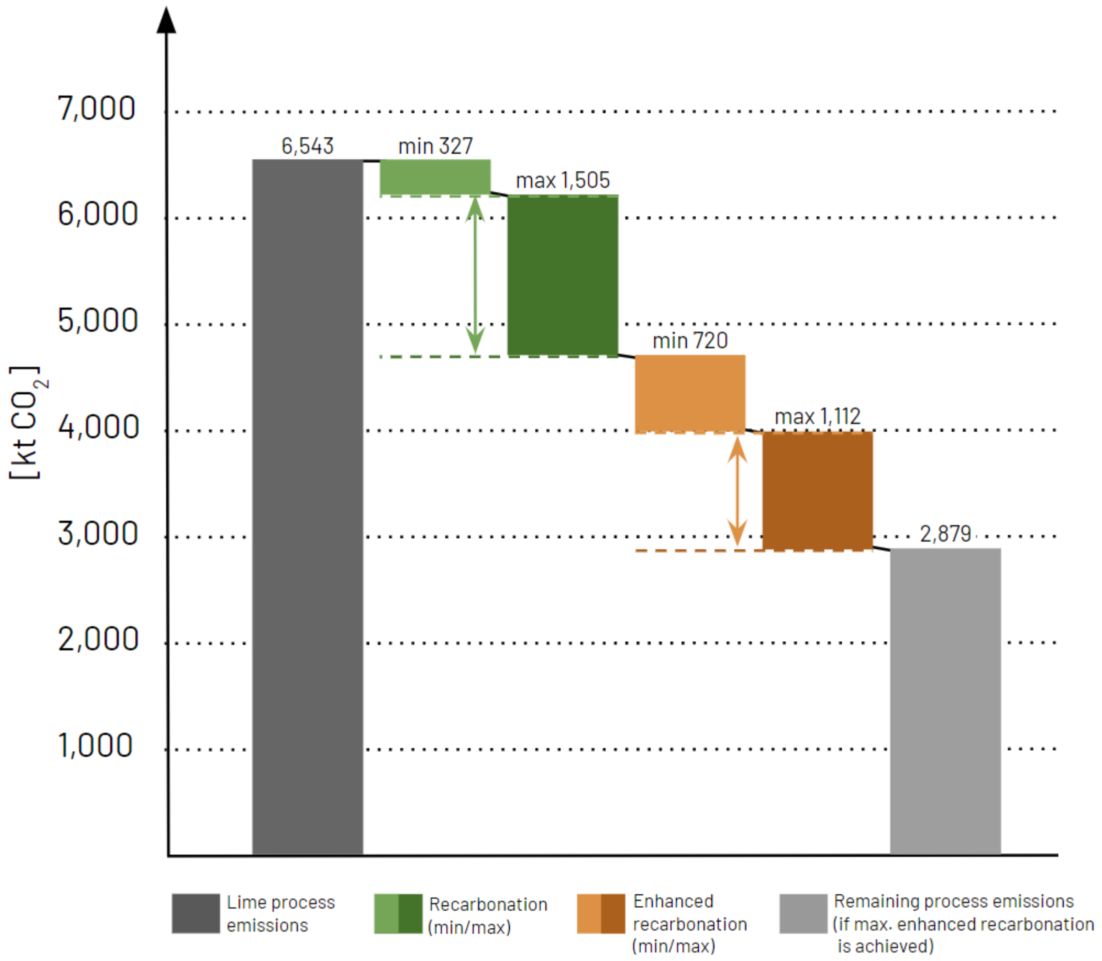

Figure 4: Comparison of the CO_2 emissions from lime production in the iron and steel industry (excluding fuel combustion emissions) driven by the lime demand in the iron and steel industry, with the current minimum and maximum recarbonation levels, as well as the potential range achievable through enhanced recarbonation efforts.

1.3.2. Sand lime bricks

Sand lime bricks, also known as calcium silicate bricks, are primarily used in the construction industry due to their durability, strength and environmental friendliness. In Germany, SLBs are extensively used in the multi-storey residential building sector, providing high-quality yet affordable housing. These bricks are made from a mixture of lime, sand and water, which undergoes high-pressure steam curing, forming calcium silicate hydrate (CSH), the binder that gives SLBs their structural integrity.

Carbon sequestration potential

Over their lifetime, SLBs naturally absorb CO_2 from the atmosphere through recarbonation. The calcium silicate hydrates formed during the production process react with CO_2, converting it into calcium carbonate ($CaCO_3$), thus sequestering CO_2. This process is estimated to absorb approximately a third (141 kt CO_2) of the quantity of CO_2 emitted by lime production in Europe.[4] The carbonation process occurs gradually throughout the bricks' lifespan and the presence of coatings or plaster may slow it down. However, when SLBs are demolished and crushed for recycling, the increased surface area enhances recarbonation.

Techniques for enhanced recarbonation

Enhanced recarbonation aims to increase the CO_2 absorption of SLBs by optimising environmental conditions such as CO_2 concentration, temperature and exposure to atmospheric conditions. This can be achieved by recycling SLBs after their use, particularly by crushing them to expose more surface area to the air, allowing for faster carbonation. Enhanced carbonation is especially effective after the bricks' service life when they are reused in different applications such as road construction or concrete aggregates. Enhanced recarbonation potentials in SLBs are still uncertain and are therefore not included in Figure 5. Further research is needed to optimise these processes for large-scale industrial use.

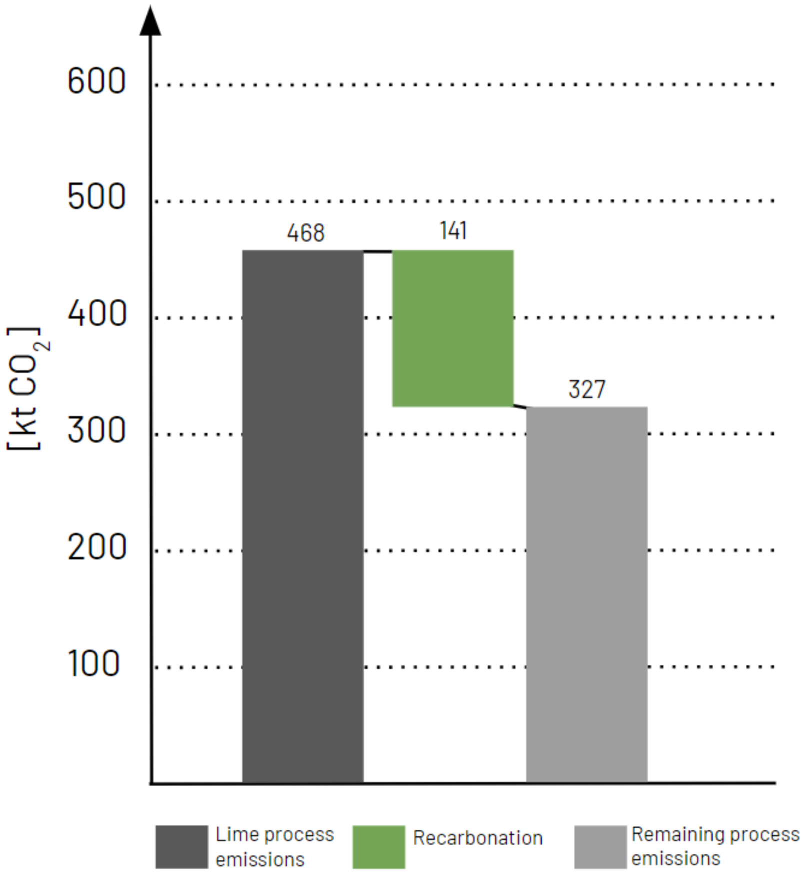

Figure 5: Comparison of the CO_2 emissions from lime production in sand lime bricks (excluding fuel combustion emissions) and recarbonation potentials during the bricks' lifetime.

1.3.3. Flue gas treatment

A flue gas treatment system is employed in combustion plants, particularly coal-fired power plants and waste incineration facilities, to remove acid gases such as nitrous oxides, sulphurous oxides and hydrofluoric acids from flue gases. Lime is a key reagent in these systems, where, as it is highly alkaline, it reacts with these acid gases to remove them. The capture of CO_2 happens alongside the removal of the acidic gases, capturing the CO_2 as part of the reaction products. The efficiency of CO_2 capture can vary depending on the process conditions, such as temperature, pressure and the specific type of lime used. Figure 6 indicates emission, recarbonation quantities and enhanced recarbonation potentials.

Carbon sequestration potential

Recarbonation: Lime is used to capture CO_2 directly and instantaneously within the flue gas stream, effectively reducing emissions at the source. This immediate reaction sequesters carbon as calcium carbonate, capturing approximately 32% of the CO_2 emitted during the lime's calcination process.

Enhanced recarbonation: Air Pollution Control Residues (APCRs), the residues left behind after acid gases have been absorbed, are treated after their initial use in flue gas treatment. This process captures an additional 27-34% of CO_2 directly from the atmosphere, further contributing to emission reduction.

Techniques for enhanced recarbonation

Enhancement in a controlled environment: APCRs can be placed in curing chambers that simulate or accelerate recarbonation processes. This might involve controlling the temperature, pressure and humidity to optimise the reaction rate.

Sequestration from the atmosphere: In contact with atmospheric CO_2, APCRs continue to capture and convert CO_2 into solid carbonates. This process can take place over several days to weeks, depending on the conditions, allowing the residues to sequester additional CO_2 from the atmosphere, beyond what was captured during the initial flue gas treatment.

After enhanced recarbonation, the APCRs, now enriched with carbonates, can be repurposed in building construction materials, such as concrete and aggregate, thereby permanently sequestering carbon in a stable form and reducing the carbon footprint of construction activities. This dual approach of immediate recarbonation and subsequently enhanced recarbonation maximises the carbon sequestration potential, contributing to both immediate emission reductions and carbon removals.

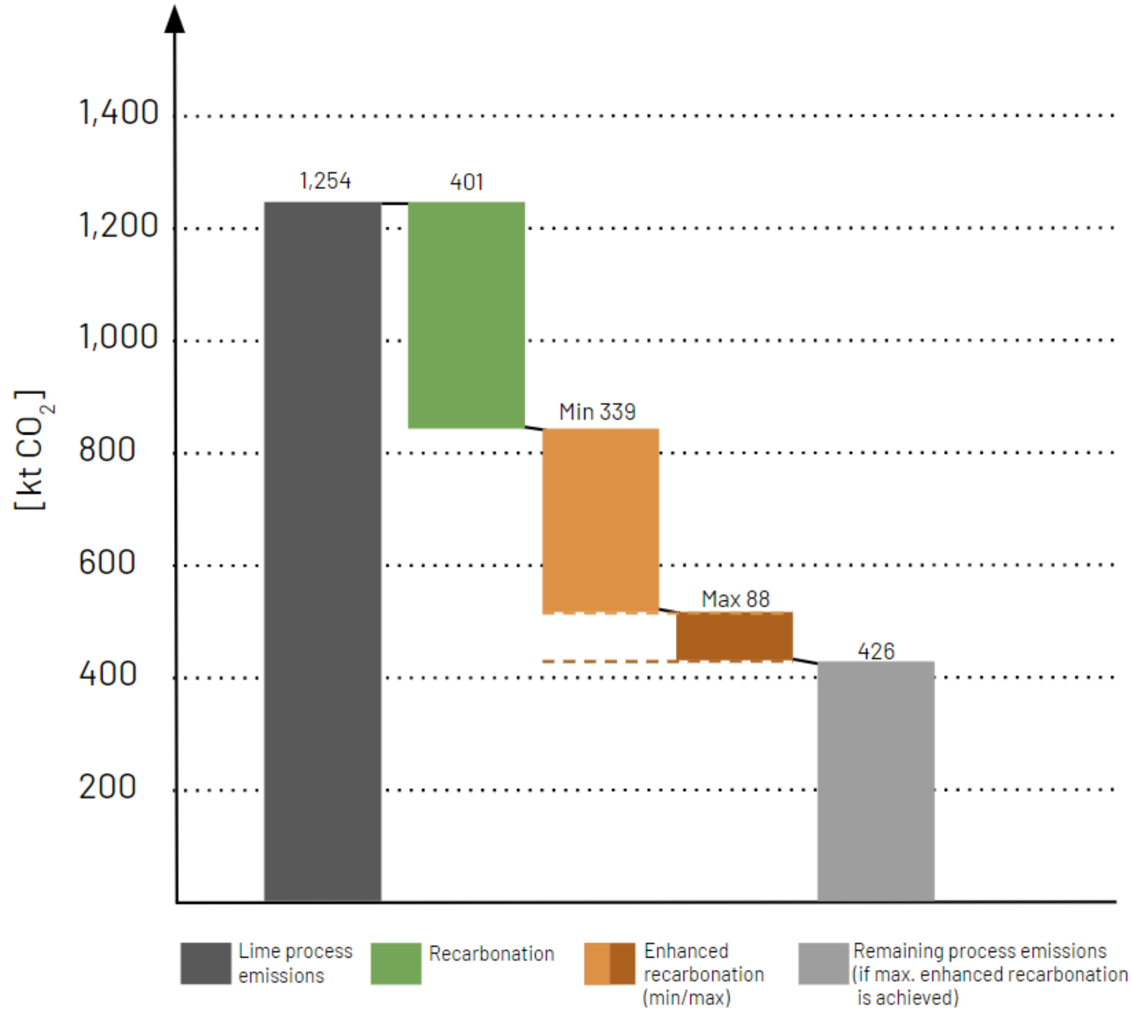

Figure 6: Comparison of the CO_2 emissions from lime production in flue gas treatment (excluding fuel combustion emissions) driven by the lime demand in flue gas treatment with instantaneous recarbonation levels, directly reducing the facilities' emission, as well as the potential range achievable through enhanced recarbonation efforts.

2. Carbon accounting of recarbonation within carbon markets

Carbon markets can play a central role in realising lime's full climate mitigation potential. A robust carbon accounting of lime's emissions is a prerequisite for achieving the emission reduction potential in the short term and enabling carbon removals in the long term.

Currently, carbon accounting standards within compliance and voluntary markets properly account for the emissions resulting from lime production; however, they ignore the re-absorption of CO_2 (i.e., recarbonation) from lime products' use and end-of-life phases. As a result, the quantification of the greenhouse gas (GHG) emissions of lime products is incomplete. Such an incomplete quantification of the life-cycle emissions of lime may hinder potential emission reductions in industry. For example, if lime products' emissions are consistently overestimated within compliance or voluntary markets, this may lead to incentives to replace lime products with other alternatives that may seem more beneficial for the climate. The incomplete quantification also fails to incentivise emission removals, which could be achieved through the adoption of enhanced recarbonation activities and more broadly, the possibility of transforming an industry from a source to a net sink of emissions.

Carbon markets are carbon pricing mechanisms established to incentivise GHG emission reductions by assigning a monetary value to CO_2 and other greenhouse gases. They create a financial incentive for companies and other entities to reduce their emissions, either by limiting the amount of emissions they are allowed to emit or by allowing them to offset their emissions through market-based mechanisms. These markets fall into two broad categories:

1. Compliance markets: Legally mandated schemes where companies must comply with specific regulations, often under a cap-and-trade system and thus pay for the CO_2 they emit.
2. Voluntary carbon markets (VCMs): Schemes driven by organisations or individuals seeking to offset their carbon footprint out of corporate responsibility or consumer demand.

Carbon markets can help substantially reduce the costs of climate mitigation to meet the 1.5℃ target of the Paris Agreement (PA).[9] Achieving this ambitious goal requires steep emission reductions and also the removal of CO_2 from the atmosphere.[10]

Compliance markets

Compliance markets are established by governmental or transnational bodies to meet legally binding emission reduction targets. A prominent example is the EU ETS, which operates on a cap-and-trade principle. It is a crucial climate policy instrument in the EU's strategy to combat climate change and has become a model for similar systems worldwide. Under the EU ETS, a cap is set on the total amount of certain GHGs that can be emitted by installations covered by the scheme. Companies receive or buy emission allowances within this cap and can trade these allowances as needed. The cap is reduced over time, incentivising companies to invest in cleaner technologies to meet their emission reduction targets. Currently, the EU ETS only covers fossil emissions, as

[9] UNEP (2021). Emissions Gap Report. https://www.unep.org/resources/emissions-gap-report-2021

[10] IPCC (2022). Climate Change 2022: Mitigation of Climate Change: Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg3/

biogenic emissions are considered carbon neutral and therefore do not need to be reported. Participants can only reduce their obligations to surrender allowance and thus reduce compliance costs by cutting these fossil emissions.

The EU ETS does not recognise carbon removals, which excludes the possibility of acknowledging the benefits of recarbonation and enhanced recarbonation in lime products, by-products and wastes. Currently, carbon sequestration through recarbonation is not covered by the EU ETS unless it occurs within the same installation. However, since recarbonation and enhanced recarbonation typically take place outside the installation during the material's use phase, this process falls outside the scope of the EU ETS.

Voluntary carbon markets

Voluntary carbon markets allow companies, governments and individuals to purchase carbon credits to offset their emissions, support climate projects, or achieve sustainability goals, usually beyond any regulatory requirements. These markets operate independently of mandatory compliance schemes and are often driven by corporate climate commitments or consumer preferences. VCMs, which cover emission reductions and removals, offer flexibility and innovation, allowing for a wider range of project types to monetise the emissions reductions and removals and in doing so, make such projects viable. Project types include reforestation, renewable energy and, increasingly, carbon removal technologies.

While reduced negative carbon impacts and reported emissions under the EU ETS lead to a reduced obligation to surrender allowances and hence less compliance costs, emission reductions or removals under the voluntary schemes must follow robust carbon accounting methodologies before they can be monetised through carbon credits. Methodologies are standardised protocols and frameworks used to quantify, verify and certify emission reductions or removals that are eligible for carbon crediting. These methodologies define how projects can calculate their GHG emission reductions or removals, ensuring that the claimed environmental benefits are real, measurable and additional to what would have occurred in the absence of the project. The volume of CO_2 reduction or removal credits that can be issued to a project are determined by the difference between the CO_2 emissions that would have been emitted or remained in the atmosphere in the absence of the project activity. Regulatory bodies or standards organisations, such as the United Nations Framework Convention on Climate Change (UNFCCC) or organisations such as Verra, Gold Standard, or Puro.Earth, oversee and approve these methodologies.

At the EU level, The EU expert group on carbon removals currently advises the EU on the adoption of carbon accounting methodologies for carbon dioxide removal within the scope of the Carbon Removals and Carbon Farming Certification (CRCF) Regulation.

Principles and criteria of the VCM and CRCF

The VCM is built on a rigorous framework to uphold the integrity of carbon credits. The VCM focuses on transparency, permanence, additionality and environmental integrity, ensuring that carbon credits genuinely reflect CO_2 reductions or removals. Based on the same principles as the VCM, the CRCF is being developed within the European Union to certify carbon removals, potentially including enhanced recarbonation, as part of the EU's broader climate strategy. The CRCF introduces specific criteria such as quality, additionality, long-term storage and sustainability, known as the QU.A.L.ITY criteria, aiming for accurate measurement and lasting climate benefits. The QU.A.L.ITY criteria reflect elements consistent with VCM standards that align with the International Carbon Reduction and Offset Alliance[11] (ICROA).

Table 1: Alignment of CRCF QU.A.L.ITY Criteria with ICROA Standards

QU.A.L.ITY Criteria	ICROA Criteria	Relevance for recarbonation
QU. (Quality) Ensures quality through rigorous measurement, monitoring, verification and transparency in project data and processes.	**Quantification and Monitoring, leakage and transparency** Requires precise quantification and third-party verification of emissions reductions, along with transparency in methodologies and reporting.	**Recarbonation** is an inherent part of the lime cycle. As such, its climate impact should be quantified. **Enhanced recarbonation**, which increases CO_2 absorption, should be possible to quantify.
A. (Additionality) Aligns by requiring that projects demonstrate additionality, ensuring that the benefits are beyond business-as-usual activities.	**Additionality** Demands that carbon reductions are additional, with proof through baseline scenarios and independent assessments.	In general, **enhanced recarbonation** is additional whereas recarbonation is not. **Recarbonation** could be additional only if the mitigation activity consists of lime products replacing other alternatives.
L. (Long-term Impact) Focuses on long-term impact, implementing legal and financial protections to ensure the sustainability of carbon sequestration.	**Permanence** Emphasises permanence, ensuring carbon sequestration that is credited is durable and backed by safeguards against reversal.	**Recarbonation** and **enhanced recarbonation** permanently sequester carbon in most lime applications and products by forming calcium carbonate. As long as the carbonates are not exposed to very high temperatures (> 900°C, the likelihood of $CaCO_3$ decomposing and releasing the CO_2 sequestered back into the atmosphere is negligible.
ITY. (Sustainability) Requires projects to deliver broader co-benefits and ensures transparency through public documentation and reporting.	**Social and environmental safeguards** Ensures projects provide social and environmental benefits and maintain transparency in all project aspects.	The use of waste (i.e. steel slag) as a substitute for clinker in concrete already contributes to a **circular economy**.

Application to lime products and enhanced recarbonation

Lime products, particularly in construction, present significant opportunities for enhanced recarbonation. By optimising lime-based products or engaging in additional efforts to increase CO_2 absorption these activities can align with VCM standards, ensuring recognition and potential revenue through carbon credits. Adhering to the QU.A.L.ITY criteria under the CRCF would further integrate recarbonation projects into the EU's climate strategy, ensuring long-term support and credibility.

[11] The ICROA is a global organisation that sets and promotes rigorous standards for carbon reduction and removal activities, ensuring these efforts are credible, transparent and effective in mitigating climate change.

Emission reductions and removals

Standards and methodologies within carbon markets quantify CO_2 mitigation impact, which can be classified as emission reductions or removals. Reductions lower the amount of CO_2 emitted into the atmosphere through actions such as improving energy efficiency or using renewable energy. Removals, on the other hand, entail the capture of CO_2 from the atmosphere and storing it in another reservoir. Conventional land-based CDR methods, such as afforestation and soil carbon sequestration, increase the amount of carbon stored in vegetation and soils, respectively. Novel technical CDR methods such as direct air capture and storage (DACCS) or bioenergy with carbon capture and storage (BECCS) store CO_2 in geological formations.

Different CO_2 origins, from fossil or biogenic sources, can lead to either reductions or removals, depending on the flow of the CO_2 (Figure 7). Fossil CO_2 is produced by the combustion of fossil fuels such as coal, oil or natural gas, which releases carbon which has been stored underground for millions of years. Capturing and storing fossil CO_2, from a power-generating coal-fired power plant, with CCS helps prevent additional CO_2 from entering the atmosphere, resulting in an emission reduction. Biogenic CO_2 originates from biological sources, such as plants, animals and other organic matter and is part of the natural carbon cycle. When biogenic CO_2 is captured and stored, from a biomass combustion power-generating plant, it can potentially result in removals[12] because the carbon was originally absorbed from the atmosphere by plants during photosynthesis.

[12] If the biomass is not sourced sustainably, for example by deforestation to harvest it, the carbon stored in the trees and soil is released, resulting in additional emissions. This ultimately means that CCS of biogenic CO_2 does not have the desired effect of effectively removing CO_2 from the atmosphere. When sourced sustainably, a constant carbon stock is maintained and leads to no increase in emissions during the sourcing of biomass. .

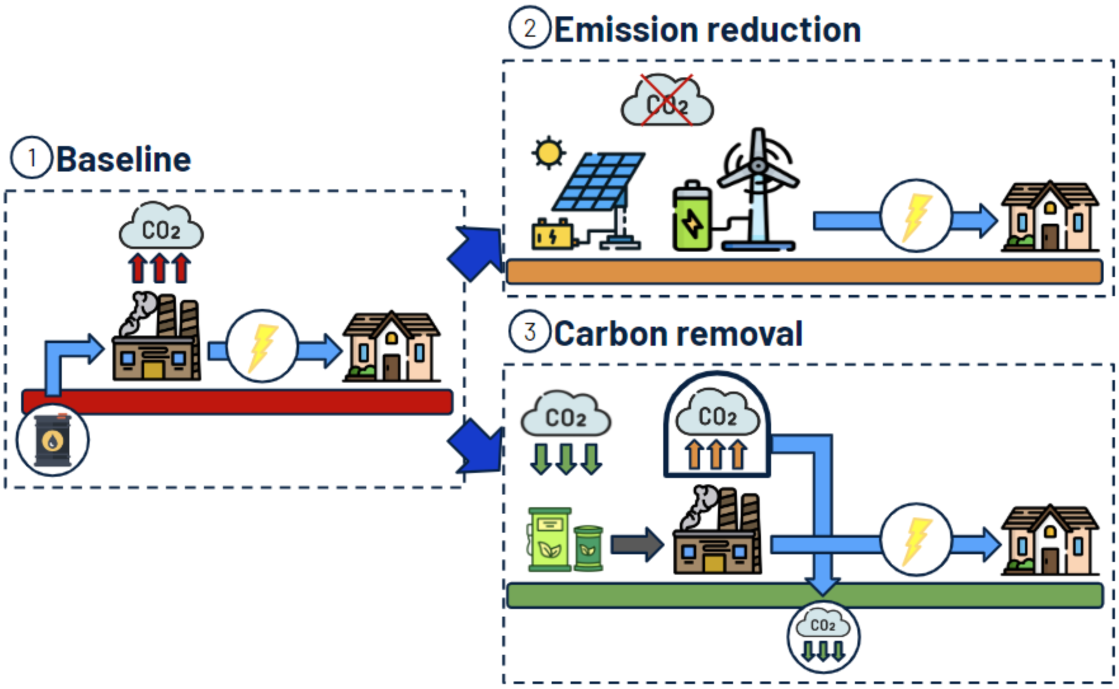

Figure 7: Emission reductions and carbon removals. 1) Baseline: In a business-as-usual scenario in the absence of a carbon project, a fossil fuel-powered electricity plant supplies homes with electricity, releasing CO_2 into the atmosphere. 2) Emission reduction. Compared to the baseline, renewable energy sources generate electricity with lower CO_2 emissions, thereby reducing atmospheric emissions. 3) Carbon removal. A bioenergy plant, such as a bioethanol facility, produces electricity from sustainably sourced biomass. The CO_2 released is carbon neutral, as it originated from the atmosphere and was absorbed by the biomass. This CO_2 is captured and stored permanently underground, making the process carbon-negative and reducing atmospheric CO_2.

Leakage in the carbon accounting of lime products

Leakage (Figure 8) occurs when a project designed to reduce emissions in one area causes an unintended increase in emissions elsewhere. In the selected case of lime used in the iron and steel industry and in the case of APCR from flue gas treatment, carbon leakage could occur if baseline recarbonation is not accurately quantified. Enhanced recarbonation activities, where CO_2 is injected into iron and steel slags or APCR, may affect the recarbonation that would have occurred without intervention. This could lead to an overestimation of sequestered carbon, resulting in the issuance of excessive carbon credits and unfairly rewarding project owners for a process that would have occurred without their efforts.

Credits can only be awarded for climate mitigation efforts that result from deliberate and additional interventions rather than processes that are already occurring. In the scenario described above, where a project aims to sequester carbon in building materials, projects need to account for the recarbonation process that takes place over the lifetime of the exact material used in the final building materials.

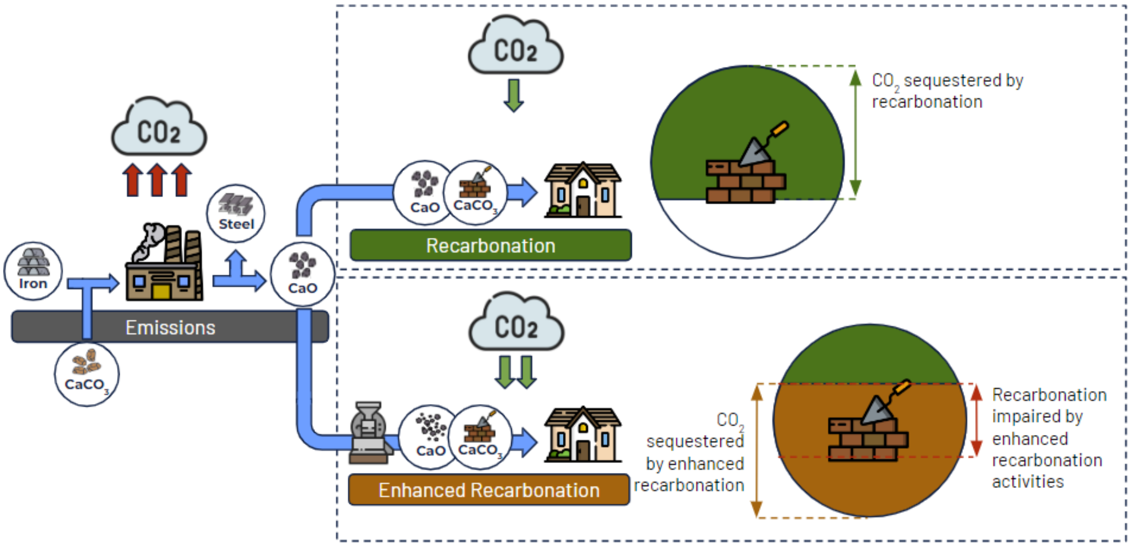

Figure 8: Importance of precise accounting of recarbonation. Recarbonation (top right) occurs under business-as-usual scenarios (baseline), with carbon being sequestered in iron and steel slags and utilised in building materials. Enhanced recarbonation (bottom right) involves the additional steps of grinding and possibly curing the slags in a CO_2 chamber, with the resulting material used in construction materials. These additional efforts could be monetised under the VCM. However, without quantifying the recarbonation in the baseline, the recarbonation that would have happened in the absence of a carbon project is impaired and the monetised impact of the project is overestimated. The two circles (right) represent the maximum CO_2 uptake potential of the lime from the iron and steel slags.

2.1. Status of carbon accounting of recarbonation

Current carbon accounting frameworks within compliance and voluntary markets do not recognise the recarbonation process in lime products or they do it to a limited extent. This incomplete accounting of the lime's climate impact, largely due to the complexity of quantification, results in an overestimation of the lime industry's carbon footprint. For the lime industry to fully realise its climate mitigation potential, both compliance and voluntary carbon markets would need to complement their frameworks to account for recarbonation happening during the use and end-of-life phase. Such inclusion would support the adoption of products with lower overall climate impacts such as low-carbon building materials.

Inclusion of recarbonation under the European Emission Trading System

The European lime industry is regulated under the EU ETS, where lime production emissions are quantified and need to be reported (i.e. emissions from combustion plus process CO_2 emissions). However, CO_2 from the air that is absorbed by a material containing unreacted lime is not accounted for.

There is a precedent in which the EU has accounted for carbon capture through immediate recarbonation in industrial processes under the EU ETS framework. Companies can reduce their carbon liabilities by binding CO_2 in products such as precipitated calcium carbonate (PCC), where the CO_2 is not immediately emitted, thus temporarily reducing atmospheric release. In this case, a company argued that captured process CO_2 that is transferred to another facility for the production of PCC, where the CO_2 is chemically bound by lime, should not be considered an emission. Rather than absorbing CO_2 from the atmosphere over time, lime works as a binding agent, instantaneously absorbing CO_2. The European Court of Justice agreed and struck down parts of the EU ETS regulation that counted this CO_2 as an emission from lime production, even though it wasn't released into the atmosphere.[13] The ruling emphasised that CO_2 chemically bound in PCC is not immediately emitted and therefore should not be reported as an emission. However, it is questionable whether the CO_2 in the PCC is permanently stored in industries such as the paper industry, which uses the PCC as a filler and coating pigment, as the paper reaches the end of its life and releases its CO_2 from the PCC through the combustion of waste paper. Therefore, the lime-bound CO_2 emission is moved from an industry and does not need to be reported, to an industry where the CO_2 quickly finds its way back into the atmosphere.

In May 2023, the EU Commission adopted its regulation to address the non-permanence of CO_2 in storage in PCC. The regulation change states that greenhouse gases not directly released into the atmosphere will be treated as emissions under the EU ETS and allowances must be surrendered unless the gases are stored or are permanently chemically bound in a product. The European Commission will have the power to set the conditions under which gases are considered permanently bound, potentially including the need for carbon removal certificates. The regulation broadly defines post-use activities to cover all actions after a product's end-of-life, including reuse, remanufacturing, recycling and disposal methods such as incineration and landfill.[14]

Unlike the PCC process, the lime applications presented in this document result in the permanent storage of CO_2, effectively removing CO_2 from the atmosphere, forming calcium carbonate and storing it either in building materials or being landfilled. In this way, recarbonation in certain products could meet the permanence requirement of the new regulation if it can be demonstrated that the risks of re-emitting the CO_2 into the atmosphere during the use phase or at the end-of-life are negligible.[15]

Recarbonation processes under voluntary carbon market methodologies

In the VCM, carbon accounting presents a different set of challenges. Mitigation outcomes within the VCM must demonstrate additionality; that is, they must prove that the emission reduction or removals would not have happened without the mitigation activity. Additionality, however, is not relevant in a compliance scheme such as the EU ETS. Since companies must stay below the cap and reduce their carbon emissions by any means necessary, the EU ETS is limited to measuring emissions and not emission reductions or removals. While the development of methodologies to quantify and certify CO_2 removals through enhanced recarbonation in building materials is still evolving, several methodologies have been created under various carbon standards to address this emerging area.

Need for a robust accounting approach to recarbonation

- The EU ETS largely ignores recarbonation, which leads to an overestimation of lime products' climate impact.
- The EU ETS currently still accounts for recarbonation in PPCs, even though its end-of-life permanence remains uncertain. The uncertainty of permanence may result in the underreporting of emissions into the atmosphere.

[13] The European Court of Justice - Judgement of the court

[14] Directive (EU) 2023/959 of the European Parliament and of the Council, OJ L 130, 16.5.2023, p. 134-148

[15] Mazzotti et al. (2005). *Mineral carbonation and industrial uses of carbon dioxide*. In IPCC Special Report on Carbon dioxide Capture and Storage (pp. 319-380). Cambridge University Press. https://archive.ipcc.ch/pdf/special-reports/srccs/srccs_chapter7.pdf

- In the VCM, existing carbon accounting methodologies to quantify and certify enhanced recarbonation lack accurate accounting procedures to quantify the baseline recarbonation (the recarbonation that would have happened without the enhancing activity) or even ignore it altogether, which may lead to the incorrect quantification of enhanced recarbonation activities.

2.2. Challenges and gaps

The current state of carbon accounting for recarbonation reveals two fundamental problems that undermine the integrity of compliance and voluntary markets. First, the partial exclusion of recarbonation from compliance schemes such as the EU ETS and its inadequate representation in voluntary carbon markets leaves scientifically recognised carbon sequestration processes unaccounted for. Second, there is a lack of clear differentiation between recarbonation and enhanced recarbonation as a baseline or benchmark for recarbonation. This distinction is crucial not only for accurate carbon accounting but also for ensuring that companies engaged in enhanced recarbonation are fairly credited for their efforts. As the EU develops the CRCF, properly addressing these issues will be vital for aligning carbon markets with the overarching goals of climate mitigation and achieving net-zero emissions, particularly for the building sector, where recarbonation processes occur in cement-based materials, sand lime bricks or mortars.

The iron and steel industry provides an illustrative example of market coverage, which encompasses CO_2 emissions during lime production and steel manufacturing, as well as the recarbonation of CO_2 into steel slags. These slags are then utilised as a clinker substitute in construction materials. Differentiating between two pathways:

A. Recarbonation: CO_2 absorption occurs without additional effort.
B. Enhanced recarbonation: Additional efforts such as grinding slags and curing them in a CO_2 chamber increase CO_2 absorption.

Figure 9 outlines all process steps, from lime production to recarbonation, enhanced recarbonation and their utilisation in construction materials, highlighting which market system covers each. It should be noted that emissions from EU ETS participants are not eligible for the VCM, as they are already regulated. However, emissions from enhanced recarbonation, such as the energy used for grinding and curing, are accounted for, quantified and balanced against the CO_2 removals the project achieves.

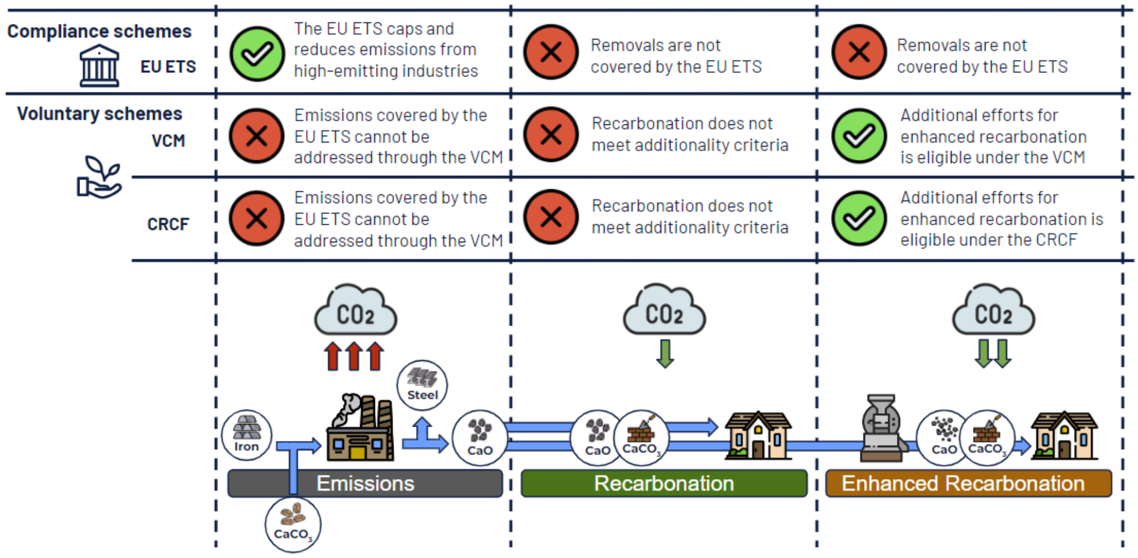

Figure 9: Overview of relevant carbon markets and their coverage of the relevant process steps throughout the lime cycle.

EU ETS exclusion of removals: The EU ETS, a compliance market, accounts for emission reductions and does not include CO_2 removals. The system focuses on reducing the release of fossil-based CO_2 into the atmosphere and excludes atmospheric CO_2 uptake through recarbonation removal processes.

Principle of Additionality in voluntary carbon markets: In the VCM, the principle of additionality is crucial for the eligibility of carbon credits. This principle requires that carbon removal or reduction activities be additional to what would have occurred in the absence of the project. If the baseline considers that lime products are produced and that recarbonation would happen, the carbon absorption from recarbonation would not be considered additional.

Emerging Carbon Removal and Carbon Farming Framework (CRCF): The CRCF, a new voluntary scheme currently under development as part of EU climate policy, aims to incentivise carbon removal and carbon farming practices by promoting the storage of CO_2 in building materials, agricultural soils and other ecosystems. In line with the principle of additionality, only enhanced recarbonation is likely to be considered as such.

The recarbonation process is currently excluded from both due to market boundary definitions in the compliance schemes and additionality principles in voluntary carbon markets, leaving the CO_2 absorption from recarbonation unaccounted for and unrewarded. This incomplete quantification leads to a lack of incentives to reduce or remove emissions.

Missed emission reduction and removal potential

The incomplete quantification of lime products' mitigation impact may hinder potential emission reductions in the industry. By ignoring recarbonation, lime products' emissions are consistently overestimated within compliance or voluntary markets.

Ignoring the mitigation potential of recarbonation may also hinder the possibility of transforming an industry from a net source to a net sink of emissions. Missed emission removal potentials include opportunities to enhance recarbonation in current lime production processes and more broadly, the opportunity to achieve carbon removals throughout lime products' lifecycle. Such opportunities are possible through the use of low-emission energy sources, coupled with low-carbon process emissions, e.g., by capturing and permanently storing process emissions via CCS. With emissions from lime production being reduced to near zero and the continued effect of lime products sequestering CO_2 from the atmosphere, the entire lifecycle of lime products could be reduced to below zero, making the lime industry a net sink of emissions. While the EU ETS already incentivises reducing energy and process emissions, there is currently little to no incentive to adopt carbon removal activities.

2.3. Quantification of potential mitigation outcomes

Figure 10 provides an overview of potential mitigation outcomes for the iron and steel industry, ranging from the baseline scenario to more advanced scenarios that incorporate renewable energy sources replacing fossil fuels and full CCS of both combustion and process emissions. Comparing the baseline scenario (Box 1, Figure 10) with the scenario where a combination of renewable fuels, CCS and enhanced recarbonation activities (Box 8, Figure 10) is implemented illustrates how the lime industry could transition from being a net source of emissions to a net sink in the future. The numbers represent the scale of the European iron and steel industry. Nevertheless, they include simplifications and therefore represent stylised pathways rather than exact scenarios.

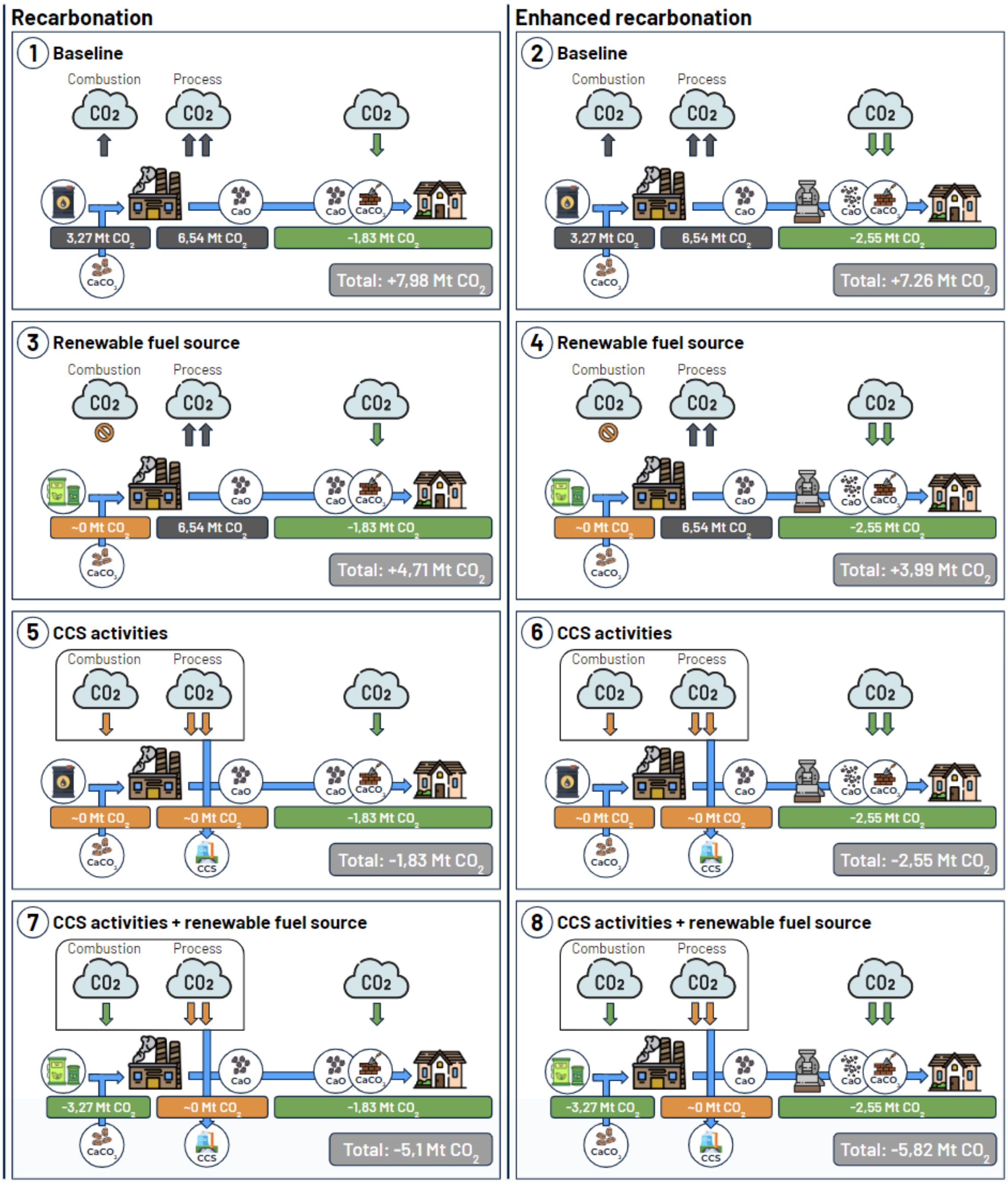

Figure 10: Potential physical mitigation outcome scenarios. Scenarios are divided into maximum recarbonation processes (left column - boxes 1, 3, 5 and 7) and minimum enhanced recarbonation activities (right column - boxes 2, 4, 6 and 8). Boxes 3 and 4 have implemented the use of a renewable fuel source, which is assumed to have negligible CO_2 emissions (equal to zero, for simplicity). Boxes 5 and 6 implemented CCS activities, capturing the entire combustion and process emissions. Boxes 7 and 8 have implemented a renewable fuel source and CCS activities. Dark grey boxes = fossil emissions; Orange boxes = zero emissions, either due to the carbon neutrality of combusted fuel or through the capturing of fossil fuels with subsequent storage; Green boxes = Carbon removals, due to the capturing of biogenic and carbon neutral CO_2 emissions, or through recarbonation and enhanced recarbonation efforts.

From a physical perspective, recarbonation and enhanced recarbonation typically lead to the permanent (for millennia) removal of CO_2 from the atmosphere. From a carbon accounting perspective, the classification may vary from case to case. As previously explained, voluntary carbon markets do not issue reduction or removal credits for processes that do not meet the additionality criteria. This means that recarbonation processes (left column, Figure 10), which achieve carbon sequestration without requiring additional activities compared to the baseline, are not recognised under voluntary carbon markets. Moreover, the EU ETS does not account for CO_2 removals and therefore, it does not recognise the recarbonation process either. As a result, the removal of up to 1.83 Mt CO_2 (the maximum recarbonation for the iron and steel example) is not accounted for (Figure 11).

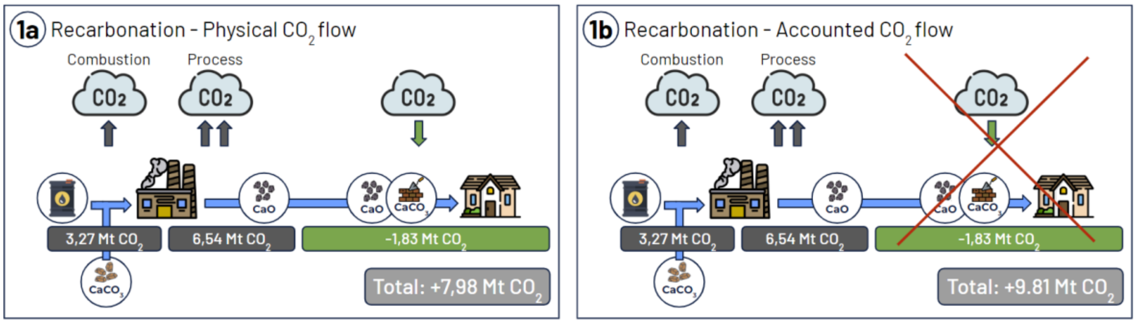

Figure 11: Physical CO_2 and accounted CO_2 flow.

Recarbonation processes are defined as not additional under voluntary schemes and not in the scope of the EU ETS. Activities towards enhanced recarbonation efforts are possible to be accounted for under the VCM and the CRCF. However, the credited mitigation outcome would only correspond to the total CO_2 absorption from enhanced recarbonation (Figure 12) minus the CO_2 absorption from recarbonation (Figure 11) that would have happened without enhanced recarbonation.

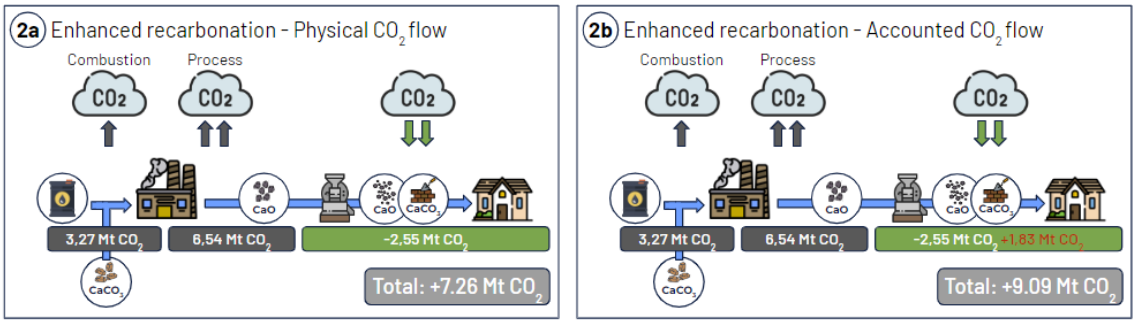

Figure 12: Physical and accounted CO_2 flow for enhanced recarbonation efforts under the VCM or the CRCF.

Even if the initial process emissions are avoided (e.g., sequestered through CCS), recarbonation is not accounted for as a removal, although the entire value chain prior to the lime products is carbon neutral and the products actively sequester carbon from the atmosphere and convert it back to calcium carbonates permanently. Again, only the enhanced recarbonation efforts minus the recarbonation quantities are eligible as removals (Figure 13).

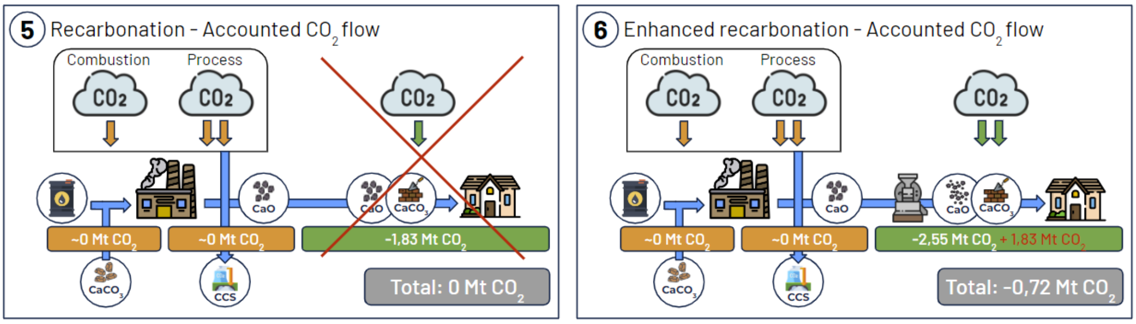

Figure 13: Accounted CO_2 flow for recarbonation and enhanced recarbonation, with CCS activities under the VCM or the CRCF.

In some lime applications, recarbonation avoids emissions into the atmosphere leading to reductions rather than to removals from the carbon accounting perspective. In flue gas systems and drinking water treatment, for example, part of the CO_2 that is emitted. is captured through recarbonation (without the need for CCS) immediately before it escapes into the atmosphere. Figure 14 illustrates the physical CO_2 flow and the accounted CO_2 flow during flue gas treatment. In this process, recarbonation occurs within the flue gas stream, instantly sequestering CO_2 along with acid gases. Additionally, further enhanced recarbonation can occur after the material's use as a cleaning absorbent. The emission reduction happens as the lime is used, although it is quite similar to the process of PCCs, it is not eligible under the EU ETS.

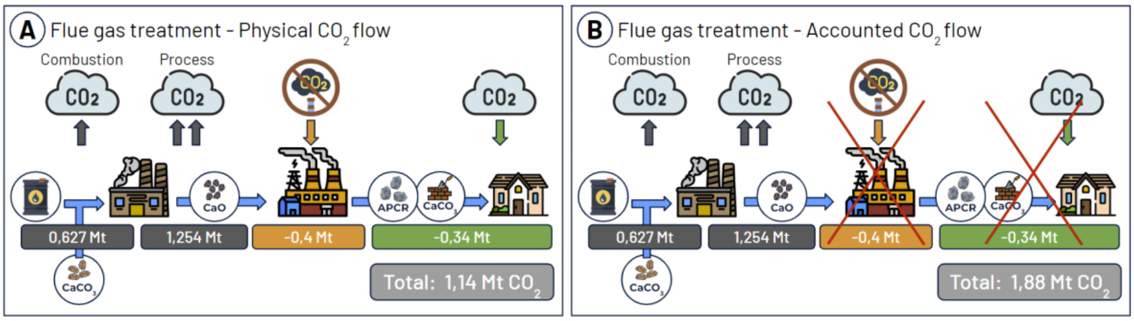

Figure 14: Physical and accounted CO_2 flows for flue gas treatment.

3. Options and key considerations for accounting for recarbonation within carbon markets

Under the current scope of the EU ETS or the voluntary carbon market, recarbonation is not recognised or accounted for, leaving a gap in today's carbon accounting frameworks. Enhanced recarbonation is considered under some voluntary market standards but with some limitations.

Recarbonation in lime products can occur as an emission reduction or removal: reduction, if the CO_2 is captured before entering the atmosphere, as it happens in the flue gas treatment case; and removal if the CO_2 is reabsorbed from the atmosphere throughout the use and end-of-life phases (both processes are illustrated in Figure 14). Enhanced recarbonation in the selected cases addressed in this paper, is typically considered a removal. The important difference lies in the additionality of the enhanced recarbonation, which is crucial to be eligible under a voluntary carbon market scheme such as the VCM or the CRCF. This section introduces various quantification measures (i.e., key considerations and recommendations) for quantifying recarbonation and enhanced recarbonation within compliance and voluntary markets. The quantification measures (Table 2) mainly focus on recarbonation, which needs greater recognition within carbon markets, as it is currently unacknowledged. Establishing recarbonation as a benchmark is essential for properly rewarding enhanced recarbonation efforts.

Table 2: Alternative quantification measures proposed for accounting for recarbonation within the EU ETS, implementation considerations, feasibility and coverage.

Quantification measure (QM)	Type of measure and effect	Feasibility	Degree of coverage
QM1: Account for instantaneous recarbonation within the EU ETS through a conservative emission factor.	The quantified CO_2 absorption through recarbonation results in a lower process emissions factor per ton of CaO produced. When applied, this results in less emission allowances to be surrendered within the EU ETS. Attribution may be a challenge because recarbonation does not occur at the plants subject to the EU ETS.	High. The emission factor could be estimated sector-wide or by application.	Med. A conservative emission factor would leave a fraction of the recarbonation unaccounted for, depending on the uncertainty.
QM2: Account for instantaneous recarbonation within the EU ETS through monitoring and measurement.		Med. Requires a robust MRV protocol to be designed and approved.	High. An MRV process would ensure that the actual CO_2 absorption amount is accounted for. For some applications and volumes of CaO-bearing materials conservative values would have to be derived, or recarbonation stays unaccounted if the uncertainty is too high, e.g. installations where the volumes of CaO-containing material generated from the lime-consuming process are low.
QM3: Account for long-term recarbonation within the EU ETS through a conservative emission factor.		High. The emission factor could be estimated sector-wide or by application.	Med. A conservative emission factor would leave a fraction of the recarbonation unaccounted for, depending on the uncertainty.
QM4: Account for long-term recarbonation within the EU ETS through monitoring and measurement.		Med. Requires a robust MRV standard.	High. Requires a robust MRV standard for long periods of time.

3.1. Carbon accounting for immediate recarbonation

One option to account for recarbonation in the case of flue gas treatment is to consider it as an emission reduction because the carbon sequestration occurs immediately during its use as an acid gas sorbent and because the CO_2 that is captured can be considered to be permanently sequestered in the spent sorbent.

A relevant precedent in this context is the case of PCCs, where the CO_2 is chemically bound in a PCC and is not counted as an emission under the EU ETS, despite the potential for eventual release under certain conditions. As the EU Commission establishes conditions under which CO_2 is considered permanently bound, the case of PCCs might become reassessed. Similar processes as in the PCC case occur in applications such as flue gas treatment, where calcium carbonates that have absorbed CO_2 are either landfilled or used in building materials. The likelihood of these materials being exposed to high temperatures that could re-release CO_2 is minimal, which makes a strong case for including lime-related emission reductions in the EU ETS.

Immediate recarbonation could be quantified, for example, through an emission factor (QM1) or precise measurements (QM2), in both cases considering the balance between the emissions during the lime production phase and the immediate CO_2 absorption during its use:

Total process emissions from lime production = Process emissions from lime production - CO_2 absorption during immediate recarbonation

QM1. Applying a downward-adjusted process emission factor, based on scientific evidence on recarbonation rates, could offer a feasible option. It could be implemented at the sector or application level, depending on the uncertainties involved. Overall, the attributed CO_2 absorption to recarbonation would need to be conservative, to avoid an overestimation of the CO_2 absorption. The choice of implementation level involves a trade-off: at the sector level, implementation is simpler but less precise, necessitating a more conservative approach, while at the application level, it allows for greater precision but is more challenging to execute. The sector-level approach would result in a single downward adjusted process emission factor for lime. An application-level approach would result in multiple emission factors for the respective lime products and applications.

QM2. Real measurements could replace the use of an emission factor. They would offer added accuracy at the expense of ease of implementation because clear monitoring and measurement procedures would need to be specified.

Both QM1 and QM2 may face implementation challenges within the EU ETS. Critically, the facilities where recarbonation takes place may fall outside the scope of the EU ETS.

3.2. Carbon accounting for long-term recarbonation

Recarbonation could be recognised within the EU ETS or beyond. In both cases, robust quantification and certification schemes must properly consider the timeframe of recarbonation and the uncertainty involved. Long-term recarbonation widely varies across different lime products, influenced by factors such as exposure conditions and durations. As in the proposed measures for immediate recarbonation, long-term recarbonation could also be quantified through an emission factor (QM3), considering the balance between the emissions during the lime production phase and the immediate CO_2 absorption during its use. One key difference is the selection of a target timeframe:

Total process emissions from lime production = Process emissions from lime production - CO_2 absorption from recarbonation during a specific timeframe

QM3: Implement a conservative, downward-adjusted process emission factor to account for the carbon sequestration from recarbonation processes. This approach could be feasible for those applications for which there is conclusive evidence of recarbonation over an extended time. It would eliminate the need to measure and account for each recarbonation process occurring in each installation and/or lime product, individually. Instead, it would allow the reduced emissions from lime production to be attributed by tracking the quantity of lime used in different applications. A proposed emission factor could be defined as the EU sector-wide process CO_2 emissions per ton of lime, adjusted by a conservative sector-weighted average to account for the CO_2 reabsorbed by lime in the final materials or products manufactured using lime. This emission factor would be grounded in conclusive and robust scientific data. This method would streamline the accounting process while ensuring that the environmental benefits of recarbonation are accurately reflected in emissions reporting.

In practice, for a short enough timeframe, emission factors that consider recarbonation would reduce the obligation of operators to surrender emission allowances under the EU ETS. This could be an option for short timeframes such as one year, a time during which absorption through recarbonation may be substantial for various applications. One limitation of this approach is that recarbonation would be quantified in advance. However, additional recarbonation after the target timeframe would remain unaccounted for.

QM4: Monitor and measure actual carbon absorption rates from recarbonation happening in each installation in which the recarbonation occurs. Recent literature reviews provide strong evidence for the effectiveness of robust measurement techniques in quantifying the carbon sequestered by various lime products.[4] Such an approach could be ideal for cases for which there is no conclusive evidence on recarbonation rates or for those cases with high variation.

Quantifying long-term recarbonation presents additional challenges, compared to immediate recarbonation:

- Recarbonation happens at the use phase, usually far from the production facilities and likely outside the scope of the EU ETS
- Defining the target timeframe entails a compromise between the amount of emission reductions that may be considered in advance and the degree of coverage of the CO_2 absorption from recarbonation
- Attribution of mitigation outcomes may be challenging
- Uncertain absorption rates for some applications

While absorption rates can vary widely, ensuring the permanence of storage is not an issue if the recarbonated materials (e.g. the steel slags) end up in a building material or a landfill and are not exposed to high levels of heat, in which case the CO_2 could be re-emitted into the atmosphere. Defining the target timeframe involves a trade-off between reductions to be considered upfront and unaccounted recarbonation potential (after the target timeframe). In key lime applications such as steel production, recarbonation rates can be quite substantial, with up to 27% of the total process emissions potentially being absorbed within the first year. Hence, a one-year timeframe may offer a good compromise.

3.3. Transitioning from a climate challenge to a climate solution

Promoting net-negative emissions

The aim is to encourage lime producers to move from being net emitters to net absorbers of carbon emissions, thereby directly contributing to the EU's net-zero targets. Lime producers can achieve zero emissions under the EU ETS by capturing all CO_2 released during lime production and using renewable energy to operate the CO_2 capture, transport and geological storage processes. Once this milestone has been reached, lime products can continue to sequester CO_2 through recarbonation or enhanced recarbonation. In such cases, either lime producers or facilities using lime products should be able to claim carbon removals through these processes. For enhanced recarbonation, mechanisms such as the CRCF offer potential solutions. However, for recarbonation to fully move lime products towards being recognised as a net-negative emission product, it needs to be recognised in carbon markets.

One potential approach could be to credit the carbon removals through recarbonation according to the downward-adjusted process emission factor. The difference between the CO_2 sequestered through recarbonation and the total process emissions current could then be multiplied by the volume of lime produced to estimate the total carbon removals occurring through recarbonation. For instance, as previously mentioned, the current process emission factor is 786 kg CO_2 per tonne of lime. Applying a hypothetical adjustment of 15% for recarbonation of lime products reduces this to 668 kg CO_2 per tonne. This difference of 118 kg CO_2 per tonne of lime produced represents the potential carbon removals, depending on the total quantity of lime products produced.

*Total potential of carbon removals = (0.15 * 786 kg CO_2/tonne - 0) * amount of lime produced*

In this hypothetical scenario, emissions generated from CCS activities, along with those produced by fuel combustion for lime production — potentially sourced from renewable energy — are excluded but would still need to be accounted for.

Collaboration towards robust MRV

To effectively integrate the benefits of recarbonation and enhanced recarbonation in the lime industry, the EU could leverage the extensive experience from robust standards, methodologies, processes and principles currently under development in the VCM. Although many of these standards and methodologies in the VCM are still evolving and not yet comprehensive, it is crucial to stay engaged with the latest developments and promptly adapt the most sound approaches also within compliance markets, particularly considering the urgent need for steep emission reductions and timely deployment of removals.

The integration of recarbonation and enhanced recarbonation could significantly benefit from robust MRV processes. Given the variability in recarbonation rates across different applications, developing tailored methodologies to accurately quantify carbon sequestration will be essential to fully realise the potential of long-term CO_2 recarbonation. This need extends beyond the lime industry to encompass any application, product, or process involved in long-term carbon sequestration. Balancing the precision of these measurements with the costs of implementing MRV systems will ultimately determine the most effective way to incorporate recarbonation into the EU

ETS. This proactive approach could help ensure that the lime industry's contributions to carbon reduction are seamlessly integrated into broader EU climate policies and possibly influence standard settings beyond the scope of the EU.

A possible opportunity for developing robust MRV processes lies within the EU Commission's Pathfinder Challenge, 'Towards Cement and Concrete as a Carbon Sink' which supports innovative technologies aimed at reducing CO_2 emissions in the cement and concrete sectors. In addition to support for technology development, support for the establishment of robust carbon accounting frameworks is essential to safely incentivise the mitigation activities needed to meet the EU climate goals. For example, overcoming the 'valley of death' — the critical phase between innovation and market adoption — is crucial for the success of carbon capture and utilisation technologies. These technologies need access to carbon markets, as their value is directly tied to CO_2 removal. Without market access, sustaining investment and scaling up after initial government funding becomes challenging. The EU could address this by involving experts in developing robust carbon accounting methodologies, ensuring technologies can effectively measure and monetise their carbon removal, securing long-term viability and impact. While the CRCF opens the door for the quantification and certification of removals, a wider set of incentives may be needed to turn the lime industry from a net source of emissions to a net sink.

Global removal developments and integration of recarbonation into existing frameworks

An alternative approach to recarbonation accounting could involve recognising recarbonation processes outside the scope of both the EU ETS and the CRCF, as today these processes are systematically excluded in existing frameworks. Both systems currently have limitations in acknowledging recarbonation fully, with the EU ETS not including long-term recarbonation or enhanced recarbonation and the CRCF primarily excluding recarbonation efforts due to the lack of additionality. The limited inclusion in both frameworks could prompt the idea of creating a special case to fully account for lime products or other materials with similar long-term carbon sequestration effects. But as the idea of inclusion of removals into the EU ETS gains momentum, creating a special case for recarbonation may be more of an interim solution.[16] A more consistent approach for the long term would be to integrate recarbonation into existing frameworks.

Preparing now by incorporating recarbonation and enhanced recarbonation into current structures is essential given the long timelines involved in the development of carbon accounting methodologies. The UK's potential approach to integrating removals into the UK ETS offers a valuable model. In this system, removals complement emissions reductions rather than replace them. When an operator removes and stores CO_2, they receive allowances that can be sold to UK ETS participants. Crucially, these allowances do not increase the overall cap on emissions; instead, an equivalent number of regular emissions allowances are removed from the market. This ensures that the total supply of allowances remains aligned with the net-zero trajectory, preserving the decarbonisation incentives for industries under the UK ETS. The UK is exploring the incorporation of CO_2 absorption through concrete into its national greenhouse gas inventories. This model, which tracks recarbonation from cement and concrete products in various applications, could provide valuable insights for carbon accounting. While primarily intended for national reporting, this approach may also hold potential for future integration into the UK ETS framework, offering an opportunity to recognise CO_2 absorption in emissions trading. However, the government is still

[16] Fridahl et al. (2023). Novel carbon dioxide removals techniques must be integrated into the European Union's climate policies. Communications Earth & Environment, 4, Article 459. https://doi.org/10.1038/s43247-023-01121-9

consulting on these possibilities and no final decisions have been made. This inclusion aims to provide a more comprehensive and accurate reflection of the country's emissions, potentially offering credits for CO_2 absorbed through concrete carbonation.[17]

The UK government's strategy of integrating removals and recarbonation into the existing compliance market could serve as an insightful reference for the EU ETS when considering how to include recarbonation and enhanced recarbonation within its own frameworks.

3.4. Conclusion

This report has highlighted the significant potential for lime products to contribute to climate change mitigation through carbon absorption from recarbonation and enhanced recarbonation. While lime production is associated with significant CO_2 emissions, the process of recarbonation - whereby lime products sequester carbon from the atmosphere - offers a critical opportunity to mitigate part of the process emissions. Enhanced recarbonation, which involves deliberate efforts to increase CO_2 absorption, can help increase climate ambition, contributing to meeting the EU's net-zero plans.

However, current carbon accounting frameworks, particularly within the EU ETS and voluntary carbon markets, do not fully account for the benefits of recarbonation. This omission leads to an overestimation of the lime industry's carbon footprint. Addressing this gap is critical and this document aims to help facilitate discussions on how recarbonation and enhanced recarbonation can be integrated into these frameworks. Implementing an emission factor that considers only recarbonation during one year may be a good compromise between accuracy and implementation feasibility, even if a fraction of the carbon absorption remains unaccounted for (recarbonation after one year). It would lay the benchmark to support policymakers, regulators and standard setters in understanding the mitigation potential of recarbonation and enhanced recarbonation, the carbon accounting gaps within carbon markets and alternative measures to close the gaps. It shows how a more comprehensive and robust carbon accounting framework could help incentivise climate mitigation activities to turn a sector from a climate challenge to a climate solution.

[17] Mineral Products Association. (2023). UK GHG inventory improvement: Carbonation of concrete emissions sink modelling (BEIS Tender Reference CR21048). Department of Energy Security and Net Zero. https://naei.energysecurity.gov.uk/sites/default/files/cat07/2307071003_UK_GHG_Inventory_Improvement_Recarbonation_Final_Report.pdf