Perspective: The European Union is not prepared for geochemical carbon dioxide removal*

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Abstract

The European Union has ambitious climate targets that may necessitate the removal of more than 500 million tonnes of carbon dioxide per year from the atmosphere by mid-century. A range of approaches have been proposed that attempt to accelerate natural rock weathering to promote "geochemical carbon dioxide removal" (gCDR), some of which are developing commercially though the voluntary carbon removal market. Progressive policy within the EU is on the verge of creating an incentive mechanism that could stimulate substantial expansion of gCDR activities, and there is world leading support for research and development to help underpin this policy agenda. Yet, there has been no systematic evaluation of the mineral resources within the EU for gCDR, or an exploration of the pathways to its efficient, equitable or cost-effective use. This manuscript makes a preliminary assessment of gCDR resources in across the EU's member states and demonstrates a CDR potential on the order of 274 – 368 million tonnes CO_2 per year based on the use of currently produced waste and by-product materials. The annual capacity could be further extended by 10's-100's million tonnes CO_2 if extraction of appropriate rock was marginally scaled up in the coming decades. There is asymmetry of resource across the EU, which will create an uneven experience of costs and benefits if these technologies were deployed. Clearly, the EU has considerable potential for gCDR, and a systematic programme of evaluation is needed to map the resource, quantify potential reserves given the trajectory of the value of carbon removal, and employ systems level analysis such that the strengths of member states can be maximised through cooperation.

Keywords: Negative emissions, carbon dioxide removal, minerals, enhanced weathering.

1. INTRODUCTION

Towards the end of 2024 the European Union (EU) published the *Carbon Removals and Carbon Farming Regulation* creating a voluntary framework for certifying carbon dioxide removal (CDR) (European Parliament and Council of the European Union, 2024). CDR includes a broad range of proposals (Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration *et al.*, 2019) for removing carbon dioxide (CO_2) from the atmosphere including managing biomass on the land surface (*e.g.*, forestation)

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and underground (*e.g.,* with regenerative agriculture), combusting biomass for energy while sequestering the produced CO_2, or operating machines that extract CO_2 directly from the air. CDR will form an important part of our response to climate change alongside rapid emissions reduction. The intergovernmental Panel on Climate Change anticipates CDR may be required to remove on the order of 10 billion tonnes (Gt) CO_2 per year by 2050, with cumulative storage on the order of 500 GtCO_2 by 2100 (Masson-Delmotte *et al.*, 2022).

Geochemical CDR ("gCDR", Campbell *et al.*, 2022; Maesano *et al.*, 2022) involves approaches that react atmospheric CO_2 with naturally occurring rocks or anthropogenic alkaline materials. These include the addition of silicate minerals to agricultural land (Beerling *et al.*, 2018) or coastal environments (Meysman and Montserrat, 2017), the reaction of alkaline wastes or by-products (steel slag, cement waste, mine waste) in engineered facilities (Renforth, 2019; Renforth *et al.*, 2024; Stolaroff *et al.*, 2005), and processes that produce reactive materials to increase ocean alkalinity (Kheshgi, 1995; Renforth and Henderson, 2017). Broadly, these approaches attempt to accelerate natural weathering, which helps to stabilize climate over millennia (*e.g.* Berner, 2001). The reactions can be simplified to those in Eq. [1-3] and show that the final repository of CO_2 is either dissolved bicarbonate ions (HCO_3^-, Eq. [1], [2] and [3]) or new solid minerals (*e.g.*, calcium carbonate $CaCO_3$, a combination of Eq. [1] or [2] and the reverse of [3]). Eq. [1] is an example of a reaction between a calcium silicate mineral, which are commonly found in basic and ultrabasic igneous rocks. Eq. [2]. Shows the reaction between calcium hydroxide, common in anthropogenic alkaline materials (cement, slag). Eq. [3]. Shows the reaction of a carbonate mineral, found commonly within carbonate rock (limestone, dolomite). HCO_3- can be a long-term storage reservoir for carbon (>1000 years) if it resides in the ocean, the chemistry of which inhibits the reverse of Eq. [3] (Renforth and Henderson, 2017). Solid carbonate minerals are stable over millions of years.

$$CaSi-O_3+2CO_2+H_2O\rightarrow Ca^{2+}+2HCO_3^-+SiO_2 \qquad \text{Eq. [1]}$$

$$Ca(OH)_2+2CO_2\rightarrow Ca^{2+}+2HCO_3^- \qquad \text{Eq. [2]}$$

$$CaCO_3+CO_2+H_2O\rightarrow Ca^{2+}+2HCO_3^- \qquad \text{Eq. [3]}$$

1.1. Mineral feedstocks

The above reactions also highlight the potential diversity of mineral feedstocks for gCDR. A summary of these is introduced below and is reviewed in greater detail by Lackner (2002). Indicative CDR potentials (in kgCO_2 t^{-1}) of these rocks are presented in Table 1. gCDR feedstock materials have been explored since the 1990's for their ability to react with CO_2 (Lackner *et al.*, 1997), and specifically for reaction with atmospheric CO_2 (Hartmann *et al.*, 2013; Renforth *et al.*, 2009; Schuiling and Krijgsman, 2006). Natural rocks are sufficiently abundant at the surface of the earth so their capacity for CO_2 sequestration is not meaningfully constrained (Lackner, 2002). Based on contemporary production Renforth *et al.*, (2011) estimated that anthropogenic materials might be about to react with ~1 $GtCO_2\ yr^{-1}$, which may increase to 3-8 $GtCO_2\ yr^{-1}$ for future production (Renforth, 2019), with a possible additional 1-4.5 $GtCO_2\ yr^{-1}$ from mine waste (Bullock *et al.*, 2021).

Basic igneous rocks are rich in magnesium and calcium but low in silica. They are typically dark-coloured, dense, and form from the cooling and solidification of magma or lava. Common examples include basalt, gabbro, and diabase. These rocks are abundant in oceanic crust and volcanic regions such as mid-ocean ridges and continental rifts. Mineralogically, basic rocks are dominated by plagioclase feldspar (typically calcium-rich varieties like labradorite) and pyroxenes (especially augite), with olivine often present in more ultrabasic forms. Chemically, they have high concentrations of iron, magnesium, and calcium. Upon metamorphism, they can transform into rocks like amphibolite or greenschist depending on pressure and temperature.

Ultrabasic rocks are igneous rocks with an extremely low silica content and are composed almost entirely of minerals rich in magnesium, iron, and calcium such as olivine and pyroxene. These rocks are typically dark, dense, and coarse-grained. Common examples include peridotite, dunite (mostly olivine), and pyroxenite (mostly pyroxenes), and typically contain accessory minerals like chromite, magnetite, and spinel. Ultrabasic rocks are found at the surface in ophiolite rock formations. When altered, ultrabasic rocks often form serpentine, talc, and chlorite, and they are important host rocks for nickel, chromium, and platinum-group metal deposits.

Carbonate rocks are sedimentary rocks primarily composed of carbonate minerals, most commonly $CaCO_3$ and dolomite ($CaMg(CO_3)_2$). These rocks form mainly through biological and chemical processes in shallow marine environments, often from the accumulation of shells, coral fragments, and other calcareous materials. The two main types are limestone, which is predominantly calcite, and dolostone (or dolomite rock), which is rich in dolomite. Carbonate rocks are typically light-coloured, relatively soft, and often contain fossils, reflecting their organic origin. Mineralogically, carbonate rocks are dominated by carbonate minerals but may also contain clay, quartz, or organic matter as impurities. Through metamorphism, they can transform into rocks such as marble, composed of recrystallized calcite or dolomite. Relatively pure calcite-rich limestones are raw materials for the cement and lime industries. The use of carbonate rocks as a feedstock for gCDR necessitates that the final repository of the formed bicarbonate is the ocean, formation of new solid carbonate minerals using these materials would not result in a net removal of CO_2. Caserini *et al.*, (2022) estimate that there are 5 trillion tonnes of limestone within 10 km of the coast globally.

Anthropogenic alkaline materials are substances that contain elevated concentrations of Ca, Mg, or Na, resulting in high pH on contact with water. They are primarily produced as byproducts or residues from industrial processes such as cement production, steelmaking, coal combustion, and mineral processing. Common examples include cement kiln dust, blast furnace slag, steel slag, fly ash, and red mud (a byproduct of aluminium refining). Mineralogically, alkaline materials are often complex and variable in composition but typically contain hydraulic and pozzolanic phases such as portlandite ($Ca(OH)_2$), oxides (CaO, MgO), calcium sulphate phases, calcium silicate hydrates (C-S-H), and glassy aluminosilicates.

1.2. Geochemical carbon dioxide removal

Geochemical CDR approaches facilitate reaction with carbon dioxide by either increasing the reactivity of a material (*e.g.*, through the reduction of particle size, and increase in reactive surface area, (Renforth, 2012; Tromans, 2008)) and/or placing the material into a more reactive environment (*e.g.*, a reactor with elevated CO_2 (Gerdemann *et al.*, 2007), elevated CO_2 injected into reactive rock formations (Matter *et al.*, 2016), soil (Beerling *et al.*, 2018), or the ocean (Renforth and Henderson, 2017). These approaches are reviewed by Campbell *et al.* (2022), Eisaman *et al.* (2023), and Kelemen *et al.* (2020), but have been summarised below. The key resources required for each approach is presented in Table 1.

1.2.1. Terrestrial gCDR approaches

Kelemen *et al.* (2020) propose three categories of approaches for reacting minerals with CO_2. "Surficial CDR" involves the above ground handling and reaction of minerals distributed over large areas. The second category, "In-situ CDR", involved the injection of CO_2 into reactive rock formations. Finally, "hybrid CDR" involve the combination of direct air capture and mineralisation.

Surficial CDR can be further characterised as either reacting minerals in soils or the landscape (enhanced weathering), the reaction of anthropogenic materials (*e.g.*, mine wastes) in controlled facilities, or the engineered production of reactive materials for oxide looping CDR.

Enhanced rock weathering (ERW) is typically implemented by spreading finely ground silicate rocks (such as basalt) over croplands, where weathering reactions with CO_2 in soil water produce stable dissolved bicarbonate ions that can be transported to oceans (Hartmann *et al.*, 2013; Schuiling and Krijgsman, 2006). A compelling benefit of ERW is its synergy with agriculture, it potentially improves soil pH, releases beneficial nutrients, and increases crop yields while capturing CO_2 (Beerling *et al.*, 2018). Empirical field trials

Table 1

Geochemical carbon dioxide removal approaches and their associated resource needs

Technology/ approach	Key physical resources required
Enhanced weathering (terrestrial)	Basic igneous rock (although some are exploring the use of ultrabasic rock).
	Access to land, particularly cropland. Transport infrastructure to connect extraction site to application area, and access to conventional mineral spreading equipment
Anthropogenic material weathering (terrestrial) Oxide looping (terrestrial)	Anthropogenic materials. Land for distributed reaction, likely lined to collect drainage waters. Carbonate minerals. Thermal energy, calcination. Land for distributed reaction, likely lined to collect drainage waters. Carbon dioxide storage locations
Hybrid CDR (terrestrial)	Anthropogenic alkaline materials and potentially ultrabasic rock. Direct air capture, and its associated resources.
In-situ mineralisation (subsurface)	Access to suitable basic or ultrabasic rock formations (100's m deep). Water, and/or seawater for coinfection. Direct air capture, and its associated resources.
Enhanced weathering (ocean) Ocean liming (ocean)	Ultrabasic rock. Carbonate minerals. Thermal energy resources for calcination.
Electrochemical (ocean)	Silicate minerals for acid disposal. Low carbon electricity sources for the electrochemical cell. A source of brine (*e.g.,* seawater or salt).
Chemical extraction (ocean)	Carbonate and silicate minerals Extractants (*e.g.,* air derived CO_2, ammonium sulphate, sodium hydroxide)

Source: Own elaboration.

in the U.S. Corn Belt have demonstrated net CO_2 removals of over 15 tons per hectare over four years, coupled with up to 16% yield increases in staple crops (Beerling *et al.*, 2024). In the EU, Carbon Neutral Initiative (Netherlands/Spain), ClimeRock (France), Greensand (Netherlands), Green Sequest (Poland), Silicate (Ireland), The Rock Flour Company (Denmark), and ZeroEx (Germany) are examples of commercial ERW projects.

Weathering and carbonation of anthropogenic materials. Anthropogenic alkaline materials (cement, slag, ash, mine tailings) are well known to react with atmospheric CO_2. The formation of solid carbonates is consistently observed in and around legacy deposits of slag (Mayes *et al.*, 2018; Renforth *et al.*, 2009) lime (Andrews *et al.*, 1997), and mine tailings (Wilson *et al.*, 2014, 2009) and is common in brownfield soils containing cement from demolition waste (Renforth *et al.*, 2009; Washbourne *et al.*, 2015). Kelemen *et al.*, (2020) suggests that it may be possible to carbonate the most reactive components of these waste materials (*e.g.*, $Mg(OH)_2$ or $Ca(OH)_2$) by passively, or through limited mechanical mixing, distributing the material in thin layers over large areas. Arca operating in Canada and Australia is a commercial example of this approach.

Oxide looping involves reacting hydroxide minerals with atmospheric CO_2. It is possible to produce oxide/hydroxide materials at industrial scale (globally >400 Mt of lime are produced annually (Apodaca, 2025)) to react with atmospheric CO_2 (see McQueen *et al.*, 2020). In this process, carbonate minerals ($MgCO_3$, $CaCO_3$) are calcined at elevated temperature to produce oxides (MgO, CaO) which are hydrated to hydroxide minerals ($Mg(OH)_2$, $Ca(OH)_2$). Spreading these hydroxide minerals into heaps exposed to atmospheric CO_2, would result in their carbonation ($MgCO_3$, $CaCO_3$). If the emissions from the production process were substantially reduced (*e.g.*, through carbon capture and storage), then there would be a net removal of CO_2 out of the atmosphere into carbonate minerals. Recycling the carbonate minerals as a feedstock into calcination would essentially transfer CO_2 from the atmosphere into the flue gas of the kiln. Calcite/8 Rivers (United States), Heirloom (United States), and Origen (UK) are developing this technology.

Hybrid CDR involves the combination of ex-situ mineralisation with elevated CO_2 provided by direct air capture or biogenic sources. *Ex-situ* mineralisation was initially proposed as a method to sequester CO_2 produced from point sources of emissions (Lackner *et al.*, 1995; Seifritz, 1990). In these processes, CO_2 would be captured and purified from a flue gas and then reacted with water and minerals at elevated temperatures and pressures. Ultrabasic rocks (given their faster reaction kinetics) were explored as the primary feedstock, in which they would need to be extracted and finely ground (<100 µm). Gerdemann *et al.*, (2007) suggest optimum reaction conditions of >150°C and pCO_2 > 100 bar. Faster reaction times, under lower temperatures and pressures has been reported for other naturally occurring (wollastonite, Gerdemann *et al.*, 2007; Huijgen *et al.*, 2006) and anthropogenic (steel slag, Huijgen *et al.*, 2005; cement kiln dust, Huntzinger *et al.*, 2009) materials. The energy-intensive nature of mineral pre-treatment (*e.g.*, grinding and thermal activation) and the capital costs of operating a reactor at elevated pressures for slow reaction kinetics, have limited its deployment at scale (Metz and Intergovernmental Panel on Climate Change, 2005). Particularly, it performs poorly in competition with relatively inexpensive disposal of CO_2 underground. However, integration of mineralisation within the cement sector may offer opportunities for direct *ex-situ* mineralisation to become competitive (Bremen *et al.*, 2022). Indirect mineralisation was proposed to overcome limitations in the reaction kinetics by dissolving or extracting the magnesium out of the rock using a strong extractant (*e.g.*, a strong acid or base) before reacting it with CO_2 (*e.g.*, Wang and Maroto-Valer, 2011; Zhang *et al.*, 2010). These alkaline materials may be directly reacted with atmospheric CO_2 (Madeddu *et al.*, 2015) or coupled to direct air capture (Ragipani *et al.*, 2022). In the EU, Blue Skies Minerals (Germany), Carbonaide (Finland), Carborok (France), ecoLocked (Germany), and Paebbl (Netherlands/Sweden) are commercial projects developing Hybrid CDR technologies.

In-situ mineralisation refers to the process of injecting CO_2 derived from direct air capture into reactive subsurface geological formations, where it naturally reacts with silicate minerals to form stable solid carbonates (Matter *et al.*, 2016). Successful field-scale demonstrations, such as the CarbFix project in Iceland, have proven that mineralisation can occur rapidly (within years). The project dissolving CO_2 in water before injection to enhance mineral reactivity and minimise leakage. As CO_2 is more soluble at higher pressures, the co-injection of water becomes less feasible with shallower injection depths. CarbFix injected into rock at depths of 400-800 m, which corresponds to a hydrostatic pressure of 40-80 bar. At these pressures 10's tonnes of water are required for every tonne of CO_2. At <50m that would correspond to 100's of tonnes of water per tonne of CO_2 (Snæbjörnsdóttir *et al.*, 2020). The application of in-situ mineralisation to the EU will require rock formations at suitable depth, with access to fresh water, and potentially seawater. 44.01 (Oman), CarbFix (Iceland), and Cella (Kenya) are commercial in-situ mineralisation projects.

1.2.2. Ocean alkalinity enhancement approaches

Ocean Alkalinity Enhancement (OAE) is a gCDR strategy that involves adding alkaline substances (like crushed minerals or alkaline solutions) to the ocean. This process enhances the ocean's ability to absorb and store atmospheric CO_2 as dissolved bicarbonate and carbonate ions. It could also help to ameliorate ocean acidification. OAE approaches are reviewed in Renforth and Henderson (2017) and Eisamann *et al.*, (2023). See Oschlies *et al.*, (2023) and references therein for considerations on the broader environmental and social implications of OAE. The taxonomic classification in Lee Pereira *et al.*, (2025) has been simplified and adapted below.

Coastal enhanced weathering involves spreading ultrabasic rock onto coastal environments (Meysman and Montserrat, 2017; Montserrat *et al.*, 2017), in which wave action, lower pH of surface sediments, and rapid replenishment of coastal waters is thought to accelerate mineral dissolution (Schuiling and de Boer, 2010). Experiments suggest that high olivine concentrations in the sediment could result in a reduction in alkalinity (Fuhr *et al.*, 2021), suggesting care should be taken when distributing the material. Collisions between particles, *e.g.*, through wave action, may also accelerate the dissolution and reaction of the mineral (Flipkens *et al.*, 2023). Vesta (United States) is commercially developing this technology.

Ocean Liming involves the intentional addition of alkaline materials, particularly hydrated lime ($Ca(OH)_2$), to seawater (Kheshgi, 1995; Renforth *et al.*, 2013). In this process, carbonate minerals are used as the feedstock and transformed through calcination and hydration into $Ca(OH)_2$. The hydrated lime is added to the ocean via ships. For this process to contribute to CDR, the emissions at the lime kiln need to be substantially reduced (Foteinis *et al.*, 2022). Rapid mixing within the wake of a ship quickly dilutes the added alkalinity (Caserini *et al.*, 2022). Limenet (Italy) are exploring the commercialisation of a variant of ocean liming.

Electrochemical approaches involve splitting seawater or brine into acidic and alkaline streams using electrodialysis (Eisaman, 2024) or membrane electrolysis (Rau *et al.*, 2013), followed by managing or neutralizing the acidic by-products and returning the alkaline-enriched water to the ocean. The elemental reservoir of the ocean is practically unlimited for electrochemical approaches, but pretreatment of the seawater or upgrading its salinity pose practical challenges to its implementation. The high electricity demand for electrochemical systems, means that they will only be effective for CDR if they operate on low-carbon electricity sources (Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration *et al.*, 2019). Ebb Carbon (United States) are commercialising a method of electrochemical OAE.

Enhanced extraction techniques include a range of treatments to create more reactive forms of alkalinity that can be added to the ocean. These include digesting carbonate rocks under elevated CO_2 derived from DAC or biomass (Rau, 2011), high pH digestion of ultrabasic silicate rock (Madeddu *et al.*, 2015), the conversion of carbonates into hydrated carbonates (Renforth *et al.*, 2022) or extraction through ammonium sulphate (Nduagu *et al.*, 2012). Calcarea (United States) are commercialising a method of carbonate rock digestion under CO_2 rich flue gases onboard ships, Cambridge Carbon Capture (UK) are commercialising a method of alkaline digestion of silicates, and the Planeteers (Germany) are exploring hydrated mineral carbonate OAE.

1.3. Climate change mitigation in the European Union

The EU is a global leader in climate change mitigation, guided by an ambitious policy framework and robust research agenda. At the centre of EU climate policy is the European Green Deal, aiming to make Europe a net-zero continent by 2050. The European Scientific Advisory Board on Climate Change, established in 2021 by the European Climate Law, provides independent advice to the EU. Their 2025 report *Scaling up Carbon Dioxide Removals* suggests 544–568 $MtCO_2\ yr^{-1}$ will be required by 2050 to help meet EU climate policy targets. In their view, this could be met through a combination of land use, biomass energy carbon capture and storage, and direct air capture (European Scientific Advisory Board on Climate Change, 2025). The report simplifies gCDR into enhanced weathering and ocean alkalinisation, highlighting opportunities and risks in the implementation, but acknowledging that the field is at a

Table 2

Major research projects that have recently been supported by the EU

Project	Project (Value)	Aims and objectives
NEGEM (2020-2024)	Horizon 2020 (€5.8M)	Evaluated the realistic potential of CDR to achieve climate neutrality. providing insights into their technical, environmental, social, and economic aspects.
OceanNETs (2020-2025)	Horizon 2020 (€7.3M)	Aims to assess how large-scale deployment of ocean-based CDR could contribute to achieving climate neutrality and the goals of the Paris Agreement. The project evaluated various aspects of these technologies, including their CDR potential, environmental impacts, risks, co-benefits, technical feasibility, cost-effectiveness, and societal acceptance.
GENIE (2021-2027)	ERC (€9.2M)	GENIE aims to provide a comprehensive, interdisciplinary assessment of both CDR and Solar Radiation Management technologies. Its primary goal is to inform evidence-based policymaking by evaluating the environmental, technical, social, legal, ethical, and policy dimensions of these climate intervention strategies .
RESCUE (2022-2026)	Horizon (€8.0M)	RESCUE aims to enhance our understanding of how the Earth system responds to various CDR strategies, particularly in scenarios involving temperature overshoot and subsequent stabilization.
C-SINK (2023–2027)	Horizon (€5.3M)	Aims to develop a standardized and transparent European CDR market. It emphasizes the development of robust monitoring, reporting, and verification standards and policy recommendations to ensure the credibility and long-term viability.
UPTAKE (2023–2027)	Horizon (€6.3M)	Seeks to streamline the implementation of CDR methods by assessing geographical, sectoral, socioeconomic, demographic, and temporal trade-offs. The project will develop an open and interactive CDR roadmap explorer to help stakeholders investigate strategies that minimize risks and adverse impacts on society, economies, and the environment.
SEAO2-CDR (2023–2027)	Horizon (€4.4M)	This project focuses on ocean-based CDR strategies. It aims to fill critical gaps in understanding these approaches, establish robust monitoring reporting and verification strategies, and develop stakeholder-oriented governance frameworks to support the business development and scale-up of CDR.

Source: Own elaboration.

relatively early stage of development. A similar approach was adopted by the equivalent organisation in the UK (Climate Change Committee), but in their most recent advice to government, *The Seventh Carbon Budget*, they now include an 8% contribution to 2050 CDR targets using technologies that include enhanced weathering (Climate Change Committee, 2025).

The EU offers world leading support for CDR research, with several large projects funded through a range of programmes (Table 2). In addition, the EU supported the CarbFix2 project (2017-2021, €2.2M), initially proposed to store industrial CO_2, has subsequently been commercialised as a repository for atmospheric CO_2. Carbon Gap estimates that the EU has allocated €657M to support CDR methods between 2020 and 2023 and suggest that this will need to increase to €3-6 billion over the next 15-20 years (Carbon Gap, 2025a).

Despite this investment, there is no robust overview of the EU's geological resources for gCDR, nor pathways for exploiting this resource. Such an assessment is essential to identify the barriers to gCDR scale up, to understand how resources may be efficiently managed, what technologies are nationally relevant and those that require EU-wide policy, or how the cost and benefits may be shared amongst member states.

Previous work in the UK has mapped some gCDR resources (Madankan and Renforth, 2023; Renforth, 2012), explored the potential of enhanced rock weathering (Kantzas *et al.*, 2022), and paired resources to application sites to explore realistically constrained supply chains (Madankan *et al.*, in review), see Section 3. The aim of this work is to provide an initial perspective on the gCDR resources in the EU, summarise potential barriers and opportunities for developing those resources, and suggest further work that is required to create meaningful climate CDR policy for this technology.

2. RESOURCES IN THE EUROPEAN UNION FOR GCDR

2.1. Resource deposits

The EU possesses significant natural and anthropogenic mineral resources that can support scalable and durable gCDR. A summary of the natural rock resources and a brief national overview is included in Table 3 for EU member states, and their spatial distribution is presented in Figure 1. While the carbonate rocks are largely abundant across most member states, limited carbonate resources are present in Denmark, Finland, and the Netherlands. The most suitable basic rock resources are less widely distributed, situated in only 13 of the member states. Ultrabasic rock deposits are present in only 9 of the member states.

The information in Table 3 was synthesized from observations made using a geological map (Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), 2005) with a resolution of

Table 3

An overview of the geochemical carbon dioxide removal resources in the European Union

Country	Rock outcrops				Observations from 1:1,000,000 European Geological map
	B+	B-	UB	C	
Austria		■	■	■	Triassic carbonate rocks of the Northern Limestone Alps, and ultrabasic rocks associated with Kraubath ultramafic massifs. Poorer potential basic rocks associated amphibolites.
Belgium				■	Limestones and dolostones, especially in southern Belgium (*e.g.,* the Dinant Synclinorium, (Boulvain and Coen-Aubert, 2006)). Jurassic and Cretaceous limestones in Campine Basin.
Bulgaria	■	■	■	■	Large deposits of cretaceous limestones, particularly to the north associated with the Balkan Mountains. Basic and ultrabasic rocks are primarily associated with the Rhodope Massif. The Rhodope Ophiolite includes serpentinites and metagabbros (Kozhoukharova, 2024). In North West Bulgaria, a small outcrop of the Balkan-Carpathian ophiolite complex can be found (Savov *et al.,* 2001a).
Croatia	■	■		■	Deposits of limestone constituting the Dinaric Alps to the west and south, including dolomite. Basalts and altered basalts are found in the Pannonian Basin in Northern Croatia.
Cyprus	■		■	■	The Troodos ophiolite outcrops in central Cyprus, with deposits of basalt and olivine rich basalt, gabbro, and serpentine (Geological Survey Department, 1979).
Czechia	■	■		■	Basalt deposits are present in Central Bohemian Massif (Ulrych and Štěpánková-Svobodová, 2014). A small outcrop of Silurian limestone is present.
Denmark				■	No deposits of basic igneous rock. Limited carbonate deposits, but Cretaceous chalk and limestone underlay a large proportion of Denmark with minor outcrops.
Estonia				■	Large Ordovician and Silurian limestone deposits in the north.
Finland	■		■		Large and widespread deposits of Proterozoic basalt and gabbro, with isolated outcrops of serpentinite in central Finland.
France	■	■		■	Alkaline basalts are found in the Massif Central in central France particularly Chaîne des Puy, Cantal, Aubrac, Deves, and Velay Oriental (Oyarzun and Cubas, 2021), with some small outcrops of Proterozoic gabbro in the north associated with the Armorican Massif (Caroff *et al.,* 2011). Widespread deposits of Jurassic and Cretaceous limestone in the Paris Basin, Dordogne/Lot, and Southeast.
Germany	■	■		■	The rocks associated with the Eifel volcanic range (Jansen et al., 2024) and Vogelsberg Volcanic Field are the largest deposits in central/western Germany. Jurassic limestones in Bavaria and Swabia, Cretaceous limestone and chalk in Northern Germany, limestone deposits in central Germany.

Table 3 (continued)

An overview of the geochemical carbon dioxide removal resources in the European Union

Country	Rock outcrops				Observations from 1:1,000,000 European Geological map
	B+	B-	UB	C	
Greece			■	■	Greece features significant ultrabasic (ultramafic) geological formations, primarily associated with ophiolitic complexes. Limestones (calcitic and dolomitic) are the most widespread carbonate rocks. Dolomites, marbles (metamorphosed limestones), and recrystallized limestones are also common.
Hungary	■	■		■	Limited deposits of basic igneous rock, but some basalt and limestone outcrops in Balaton Uplands National Park.
Ireland	■	■		■	A small deposit of meta gabbro Connemara complex, western Ireland (Leake Bernard Elgey, 1989). Large deposits of carboniferous limestone throughout.
Italy	■	■	■	■	Italy's igneous geology is dominated by active and extinct volcanic systems. The largest include the Roman Magmatic Province (Peccerillo, 2017), Campanian Volcanic Province (Peccerillo, 2020), Aeolian Islands, Sicily, and Sardinia. Ultrabasic rocks are present in the Internal Ligurian Ophiolites (Renna and Tribuzio, 2011). Limestone and dolostone outcrops constitute some of Italy’s mountain chains.
Latvia				■	No deposits of basic igneous rock. Carbonate deposits of limestone and dolostone are present (Dreimanis and Kārklin, 1997).
Lithuania			■	■	No deposits of basic igneous rock. Serpentinite is present in Varena Geological Provence (Motuza, 2016; Stasiulaitiene *et al.*, 2011). Chalk, limestone and dolomite are abundant.
Luxembourg				■	Some limited outcrops of limestone in central and Southern Luxembourg.
Malta				■	The Maltese islands are composed of sedimentary rock with significant limestone outcrops (Continental Shelf Department, 2023).
Netherlands					Limited rock resources for gCDR, small limestone/chalk formations around Maastricht.
Poland		■	■	■	Limited rock resources for gCDR, small basic rock outcrops in southern Poland, and limited exposure of limestone.
Portugal	■	■		■	Minor basic rock outcrops associated with Lusitanian Basin near Lisbon, Gabbros outcrop in central and northern Portugal. Basic and ultrabasic rock outcrop in Northern Portugal as part of the Morais ophiolite complex. Azores and Madeira both contain substantial basalt resources. Jurrasic and Cretaceous limestones outcrop as part of the Lusitanian Basin in Western Portugal and the Algarve Basin in Southern Portugal.

Table 3 (continued)

An overview of the geochemical carbon dioxide removal resources in the European Union

Country	Rock outcrops				Observations from 1:1,000,000 European Geological map
	B+	B-	UB	C	
Romania	■	■		■	Basic rock outcrops in central Romania associated with the Carpathian Volcanic Arc, although predominantly andesitic (Harangi *et al.*, 2007). The Balkan-Carpathian ophiolite complex outcrops in Southern Romania (Savov *et al.,* 2001b). The Southern and Eastan Carpathians also host substantial limestone outcrops.
Slovakia				■	The largest surface exposure of igneous rock is largely intermediate composition in the Neogene Volcanic Field, with minor outcrops of alkali basalt. Slovakia's carbonate rocks are primarily part of the Mesozoic sedimentary sequences within the Western Carpathians.
Slovenia				■	Limited silicate rock resources. Carbonate rocks–primarily limestones and dolomites–dominate much of Slovenia's bedrock, particularly in the Dinarides and parts of the Southern Alps.
Spain	■	■	■	■	Basic igneous rock outcrops as part of the Campo de Calatrava volcanic field in central Spain, and the Oolot Volcanic Field in Catalonia, Northern Spain. Ultrabasic rocks outcrop in the Ronda peridotite in Southern Spain (Précigout *et al.,* 2013). Ultrabasic rocks are also present in Galicia-Trás-os-Montes Zone of the Iberian massif. Carbonate rocks are widespread, particularly in Eastern and Northern Spain. Spain's gCDR resources have been explored in greater detail by (Bullock *et al.,* 2023).
Sweden	■	■		■	Large and widespread deposits of Proterozoic basalt and gabbro/ dolerite. Several limestone deposits in Southern and Central Sweeden.
Epot ($kgCO_2\ t^{-1}$)	200 400	150 300	500 900	300 400	Indicative "Enhanced weathering potential" for carbon storage as a bicarbonate ion. For carbonate formation, the storage potential is approximately 0.6x, except for carbonate rock in which additional carbon storage would not be possible (see Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration *et al.,* 2019, see Figure 7.2)

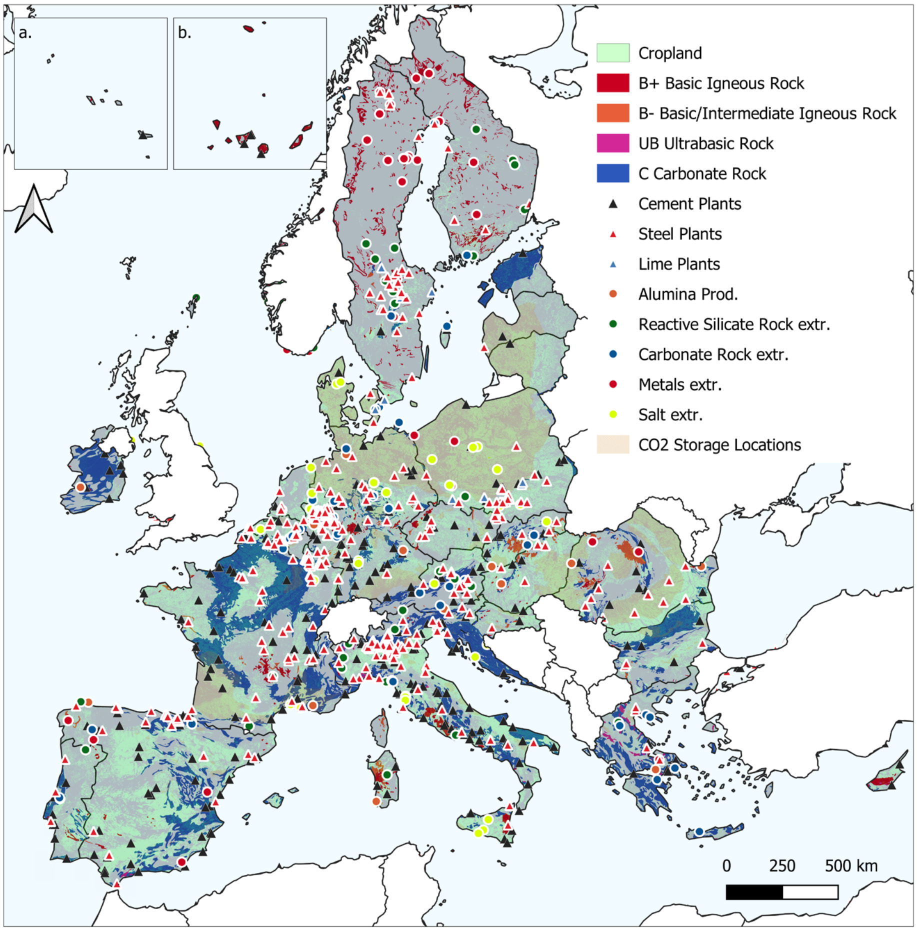
Notes: B+ includes basic silicate rocks that are relatively enriched in cations (*e.g.,* basalt). B- includes silicate rocks with intermediate composition (*e.g.,* andesite). UB denominates ultrabasic rock. C denominates carbonate rocks.

Source: Own elaboration.

1:5,000,000, and supported with additional literature where possible. It is not exhaustive, and it could miss smaller yet volumetrically significant resources. There is no consideration of what might be practically extracted, or what social or environmental restrictions may be in place for these deposits.

Figure 1

The distribution of geochemical carbon dioxide removal resources throughout the European Union member states (including a. Azores and b. Madeira/ Canary Islands). Distinction is made between basic igneous rock (*e.g.*, basalt, gabbro, dolerite) and basic/ intermediate igneous rock (*e.g.*, andesite, amphibolite, diorite) which may be less suitable for some applications



Sources: The map was created using QGIS v3.26.2, a base map of EU countries, cropland (Tubiello *et al.*, 2023), a 1:5,000,000 geological map (Bundesanstalt für Geowissenschaften und Rohstoffe [BGR], 2005) simplified with combined lithology, cement plants (Tkachenko *et al.*, 2023), steel plants (McCarten *et al.*, 2021), other production or extraction sites (Almánzar *et al.*, 2010), and CO2 storage sites (Smith, 2013).

2.2. Annual production of resources

The extraction and transformation of geological resources that have relevance for gCDR have been summarised in Table 3 including crushed rock, salt, cement, lime, and steel, with their spatial distribution shown on Figure 1.

The lithology of crushed rock production is rarely reported and the information in Table 3 represent the combined value for sedimentary (*e.g.*, limestone, sandstone) and igneous (basic, intermediate, or acidic) rocks. Such distinction is mostly unnecessary for their primary purpose of construction aggregate, yet it is essential for understanding the current capacity and scale-up potential of gCDR. The EU extracts approximately 1.2 Gt of crushed rock each year. Approximately 25% of this material will be waste "fines" <1-5mm (Mitchell, 2009), equating to around 400 Mt. Not all this material will be applicable for gCDR, but assuming 50% is carbonate rock (300 $kgCO_2$ t^{-1}) and 10-20% is basic igneous rock (200-400 $kgCO_2$ t^{-1}) then this waste material may be able to contribute 60 $MtCO_2$ y^{-1} and 8-32 $MtCO_2$ yr^{-1} of CDR for carbonate and basic igneous rock respectively.

The cement and lime industry have three mechanisms by which they might contribute to CDR. First, cement production creates waste or by-product kiln dust, equating to around 115 kg t^{-1} (Huntzinger *et al.*, 2009), which can react with CO_2. Second, cement and some lime materials may already react with atmospheric CO_2 during their service life (Xi *et al.*, 2016) or have the potential to react post-use (Washbourne *et al.*, 2015). Finally, spare capacity within kilns, reported to be 40-50% in the EU (Harder, 2023), could be used to manufacture lime for ocean liming (Kheshgi, 1995; Renforth *et al.*, 2013) or direct air capture (Erans *et al.*, 2020; McQueen *et al.*, 2020). The later two of these mechanisms requires deep emissions reduction at the production site for net removal (Foteinis *et al.*, 2022). Collectively, the EU produces around 135 Mt of cement and lime annually. Approximately 20% of current lime production applications result in a reaction with CO_2 and approximately 15% of cement may already react with atmospheric CO_2 during its service-life (see Renforth, 2019 and references therein) resulting in 12 $MtCO_2$ yr^{-1} removed from the atmosphere. Around 115 kg of cement kiln dust is produced per tonne of cement clinker, this could capture a further 4.2 Mt CO_2 yr^{-1}. The chemical decomposition of limestone represents >50% of the emissions in a cement plant, the equivalent mass of CO_2 may be recaptured if cement were carbonated following use (*e.g.*, during demolition). This could equate up to 61 $MtCO_2$ yr^{-1} based on contemporary production. Cement kilns within the EU operate below capacity (some suggesting 60% (Harder, 2023)), if this were used to produce lime for either direct capture of atmospheric CO_2 (Erans *et al.*, 2020; McQueen *et al.*, 2020) or for ocean liming (Renforth *et al.*, 2013), that would result in an additional 63-82 $MtCO_2$ yr^{-1} CDR, although the emissions from the production site would need to be substantially reduced for this to remove more CO_2 than emitted.

By-product and waste slag from the steel industry is also known to react with atmospheric CO_2 in legacy deposits (Mayes *et al.*, 2018; Pullin *et al.*, 2019; Renforth *et al.*, 2009). Accelerating this reaction with atmospheric CO_2, while simultaneously reducing steel greenhouse gas emissions, could result in a net negative steel industry (Renforth *et al.*, 2024). Approximately 140 Mt of steel is produced by the EU annually, creating 42 Mt of slag. This has the potential to react with 16 $MtCO_2$ yr^{-1}.

Table 4

Production of resources relevant to geochemical carbon dioxide removal

Country	Crushed rock prod.* (Mt/yr)	Salt prod.** (Mt/yr)	Cement prod.** (Mt/yr)	Lime prod.** (Mt/yr)	Steel Prod.** (Mt/yr)	Relevant metal mining and processing (kt yr^{-1})**
Austria	33.0	1.1	9.3	0.9	13.9	
Belgium	38.5		7.2		7	
Bulgaria	21.5		2.0	1.4	0.5	Cu – 100.0
Croatia	17.0	0.06	2.4	0.2	0.2	
Cyprus	9.5		0.3	0.005		Cu – 200(2019), Ni – 1.0
Czechia	45.0		4.5	0.8	4.3	
Denmark	0.6		2.0			
Estonia	6.5		0.3	0.03		
Finland	49.0		1.5		3.5	Cr – 1,998, Cu – 108, Ni,- 45, PGM – 1.2
France	191.0	5.5	16.0		12.1	
Germany	210.0		33.0	5.9	36.9	Al – 1,000
Greece	48.5		6.0		1.5	Al – 861, Cr - 2, Ni – 1.6
Hungary	22.0		2.4	0.2	0.9	Al - 300
Ireland	30.0		3.6			Al – 1,629
Italy	95.0	1.5	21.4	2.2	21.6	
Latvia	2.8		1.3		0.02	
Lithuania	9.3		1.4			
Luxembourg	1.1					
Malta	0.9					
Netherlands	0.0	5.9	2.5		6.1	
Poland	86.0	4.5	18.8	1.6	7.5	Cu - 443
Portugal	44.3	5.0	4.5		1.9	Cu - 32
Romania	40.5	1.4	10.2	1.1	2.6	Al - 108, Cu - 9
Slovakia	16.5		4.2	0.8	3.9	
Slovenia	11.5	2.3	1.0	1	0.6	
Spain	94.7	3.9	19	1.7	11.5	Al – 1,343, Cu - 118
Sweden	88.7		2.9		4.4	Cu – 88
Total	*1211*	*31.2*	*122.7*	*11.9*	*140.2*	*10,516.8*^{a}
Gross CDR potential (MtCO$_2$ yr^{-1})	*B+: 8-32*^{b} *C: 60*^{a}	-	*CKD: 4.2*^{c} *Ser. 9.8*^{c} *Dem.: 51.6*^{c} *Lime: 63 -82*^{d} *Total: 129 - 148*	*2*^{e}	*16*^{f}	*75 - 132*

Notes: * (UEPG, 2025). ** USGS – International Mineral Statistics and Information – 2022 (available form https://www.usgs.gov/centers/national-minerals-information-center/international-minerals-statistics-and-information - Accessed May 2025). a. Using conversion factors from (Bullock *et al.*, 2021; Renforth, 2019), Alumina (Al) 4,941 kt y^{-1}, which equates to 17 Mt yr^{-1} of red mud (128 kgCO$_2$ t^{-1}). Chromium (Cr) 2,000 kt y^{-1}, which equates to 2 Mt yr^{-1} of tailings (284 kgCO$_2$ t^{-1}). Copper (Cu) 1,089 kt y^{-1}, which equates to 577 Mt yr^{-1} of tailings (125-224 kgCO$_2$ t^{-1}). Ni – 47.6 kt y^{-1}, which equates to 0.01 Mt yr^{-1} of tailings (17-660 kgCO$_2$ t^{-1}). PGM- 1.2 kt y^{-1} this is produced from a single polymetallic mine, as an accessory to Cu and Ni production, so has not been included separately. b. For basic rock: assuming 25% of aggregate production is waste fines (Mitchell, 2009), 10-20% is basic igneous rock with appropriate rock chemistry, with a potential to remove 200-400 kgCO$_2$ t^{-1}. For carbonate, assume 50% of the fines is appropriate carbonate rock, with a removal potential of 300 kgCO$_2$ t^{-1}. (Renforth, 2019). c. Assuming 115 kg of cement kiln dust is produced per tonne of cement, with a capture potential of 330 kgCO$_2$ t^{-1}, and that 16% of cement is carbonated during service life with remainder post demolition (500 kgCO$_2$ t^{-1}, (Renforth, 2019)). d. Assuming that cement kilns operate at 60% capacity (Harder, 2023), and the remaining is used to produce lime with a carbon removal potential of 770–1000 kgCO$_2$ t^{-1} (Foteinis *et al.*, 2022; Renforth, 2019) e. The reaction with CO$_2$ is implicit within 20% of lime applications, and that it could react with 770 kgCO$_2$ t^{-1}. (Renforth, 2019). f. Approximately 330 kg slag are produced per tonne of steel, and this can remove 384 kgCO$_2$ t^{-1}. (Renforth, 2019).

There are several waste materials produced from mining that may be appropriate for geochemical CDR (Bullock *et al*., 2021). Chromium (Cr), copper (Cu), nickel (Ni), and platinum group metals (PGM) are the most significant for the EU, the typical commercial ore grades range from 2-25% (Cr), 0.2-3% (Cu), 0.2-2% (Ni), 3 x10^{-5}% (PGM). The remaining "gaunge" is composed of minerals that could be potentially used as a feedstock for gCDR technologies. In addition, the processing of bauxite for aluminium creates "red mud", a hyper alkaline waste (Renforth, 2019). The CDR potential of mine waste is dominated by waste from Cu mining in Bulgaria, Finland, Poland, Portugal, Romania, Spain and Sweeden. Table A1 provides an overview of the deposit types and their potential for CDR. Simplifying in Table 4, the potential for mine waste weathering may be on the order of 75 – 132 $MtCO_2$ yr^{-1}, although this is an initial estimate and could be substantiated with chemical analysis of the specific waste deposits.

Salt production is noted in Table 3 given that some approaches to ocean alkalinity enhancement propose to use electrochemistry to split salt into acid and base streams (Eisaman, 2024; Rau, 2008; Rau *et al*., 2013). In these technologies the base stream is added to the ocean, resulting in an increase in ocean alkalinity and a removal of CO_2 from the water, and eventually the atmosphere. The acid stream from this process would need to be neutralised by reaction with a silicate rock to operate these approaches at climate relevant scales. Approximately 31 Mt of salt are extracted and consumed annually in the EU. If electrochemical processes were to exploit mined salt to create alkalinity, at least 1.3 t salt would be required for every tCO_2. Most of the proposed electrochemical approaches use seawater as the source of brine (Eisaman, 2024; Eisaman *et al*., 2023).

The total gross CDR potential for waste materials or by-products in the EU is approximately 124-42 $MtCO_2$ yr^{-1}, and an additional 12 $MtCO_2$ yr^{-1} could already be occurring due to the reaction of lime and cement with CO_2 during their service life. If the emissions at cement kilns were net-zero, and that the spare capacity that is present in the EU were used to produce lime for CDR, then an additional 63-82 $MtCO_2$ yr^{-1} removal potential could be realised. Finally, the possibility of using mineral wastes from metal mining could contribute an additional 75–132 $MtCO_2$ yr^{-1}, the efficacy of which depends on the geology of the host rock. The total resource potential based on contemporary production is 274–368 $MtCO_2$ yr^{-1}. Upscaling rock extraction specifically for gCDR would add additional resource. For instance, a 20% increase in current rock extraction in materials that are relevant to gCDR with a capture potential 200-400 $kgCO_2$ t^{-1}, would equate to an additional 48-97 $MtCO_2$ yr^{-1} of CDR capacity.

3. NATIONAL CASE-STUDIES

There is limited exploration of gCDR for nation states, which have been summarised below. While these studies are useful for demonstrating potential and shaping policy, they do not capture nuances of resource sharing through cooperation, a strength of the EU's internal market.

3.1. Enhanced Rock Weathering in the UK

Enhanced rock weathering (ERW) is one of the more widely known methods of gCDR, which involves the distribution of crushed rock onto agricultural fields (Hartmann *et al.*, 2013; Schuiling and Krijgsman, 2006). Model simulations have shown substantial scalable potential at competitive cost, with potential secondary benefits to farmers (Beerling *et al.*, 2020), which has catalysed early-stage investment and deployment.

Deployment of ERW within the UK has received considerable attention. Initially Renforth (2012) mapped ERW resources in the UK and showing that their total capacity for CO_2 sequestration was >400 $GtCO_2$, which is much greater than any realistic future need. The calculated costs encompassed a substantial range ($€_{2024}$ 71-590), largely controlled by uncertainty in the mineral weathering rate. Kantzas *et al.*, (2022) implemented a geochemical weathering model coupled with a cost assessment to show that ERW may cost $€_{2024}$ 102-139, scale to 6-30 $MtCO_2$ yr^{-1} (the higher end of the range being equivalent to >40% of anticipated UK CDR requirements). Madankan and Renforth (2023) refined the UK resource assessment, identifying 68 current basic igneous rock production sites, their production volumes equated to around 14 Mt yr^{-1}, and that planning permission has been granted to extract 490 Mt. Finally, Madankan *et al.*, (in review) has explored extraction scenarios and demonstrated that for large scale deployment in the UK, a large flow of material across the country from production sites to agricultural land would be required. This work has led to the introduction, albeit without adoption, of ERW in UK climate policy (UK Government, 2021), and the recent advice to UK Government on the implementation of enhanced weathering into their net zero pathway (Climate Change Committee, 2025).

The global assessment of Beerling *et al.*, (2020), simulated the potential of ERW in France, Germany, Italy, Poland, Spain using their weathering model, and estimate a collective potential for 56-206 Mt CO_2 removal, for applications between 10-50% of cropland. This model predicts an annual removal rate of approximately 5.1-6.6 tCO_2 ha^{-1}.

It is challenging to obtain empirical data to validate these models given that field experiments must be undertaken over several growing seasons, across a range of soils, crops, climates, and mineral addition rates, and that appropriate protocols for measurement are still under development (Clarkson *et al.*, 2024), with mixed results reported for smaller scale experiments (Buckingham *et al.*, 2022; Reershemius *et al.*, 2023). However, measurements from field experiments suggest that annual removal rates of 1.3 - 2.6 tCO_2 ha^{-1} yr^{-1} may be possible (Beerling *et al.*, 2024; Larkin *et al.*, 2022). The first credits issued for ERW by Isometric to InPlanet for a 500 ha addition in Brazil suggests a removal rate of approximately 1.1 tCO_2 ha^{-1} yr^{-1} (although only 36% of that was claimed in the credit (Isometric, 2025)).

A simple estimate for the potential of ERW in the European Union is presented in Table 5 assuming an annual removal rate of 1 tCO_2 ha^{-1} and applied to 25-75% of national cropland.

Table 5

Resources and potential for enhanced rock weathering in the European Union

Country	Cropland (Mha)	Gross ERW potential CDR ($MtCO_2$/yr)	Total Silicate Req. (Mt/yr)	Ratio (required/ produced)
Austria	1.87	0.5-1.4	18.7	0.6-1.7
Belgium	1.26	0.3-0.9	12.6	0.3-1.0
Bulgaria	4.42	1.1-3.3	44.2	2.1-6.2
Croatia	1.42	0.4-1.1	14.2	0.8-2.5
Cyprus	0.34	0.1-0.3	3.4	0.4-1.1
Czechia	3.42	0.9-2.6	34.2	0.8-2.3
Denmark	2.63	0.7-2.0	26.3	43.9-131.7
Estonia	1.07	0.3-0.8	10.7	1.6-4.9
Finland	2.08	0.5-1.6	20.8	0.4-1.3
France	22.92	5.7-17.2	229.2	1.2-3.6
Germany	15.84	4.0-11.9	158.4	0.8-2.3
Greece	2.89	0.7-2.2	28.9	0.6-1.8
Hungary	5.41	1.4-4.1	54.1	2.5-7.4
Ireland	2.28	0.6-1.7	22.8	0.8-2.3
Italy	10.27	2.6-7.7	102.7	1.1-3.2
Latvia	1.82	0.5-1.4	18.2	6.5-19.5
Lithuania	2.90	0.7-2.2	29.0	3.1-9.3
Luxembourg	0.1	0.0-0.1	0.9	0.8-2.4
Malta	0.01	0.0-0.01	0.1	0.1-0.4
Netherlands	1.59	0.4-1.2	15.9	-
Poland	14.89	3.7-11.2	148.9	1.7-5.2
Portugal	2.32	0.6-1.7	23.2	0.5-1.6
Romania	9.99	2.5-7.5	99.9	2.5-7.4
Slovakia	1.74	0.4-1.3	17.4	1.1-3.2
Slovenia	0.33	0.1-0.2	3.3	0.3-0.9
Spain	17.96	4.5-13.5	179.6	1.9-5.7
Sweden	2.72	0.7-2.0	27.2	0.3-0.9
Total	**134.4**	**33.6-100.9**	**1345**	

Source: Own elaboration.

This could result in 34 to 100 $MtCO_2$ yr^{-1}, of which France, Germany, Italy, Poland, and Spain would contribute 70% of this potential. Even the lower estimate is significant in the context of a possible EU target of 500 $MtCO_2$ yr^{-1} by mid-century. The total basic igneous rock requirement, assuming an application of 30 t ha^{-1} would be on the order of 1.3 to 4.0 Gt yr^{-1}. The lower estimate is equivalent to total current annual rock production in the

EU, and an unquantified multiple of current basic igneous rock extraction. While the scale-up of rock production would be challenging, potentially 6-24 $MtCO_2\ yr^{-1}$ could be met using waste quarry fines (Table 3), and Madanken *et al.*, (in review) has shown that an equivalent scale up in the UK is plausible over decades. Table 3 highlights the asymmetry that would exist in Europe between member states in which rock is produced and where it may be applied. For instance, a lack of resource availability in Northern (Belgium, Denmark, Estonia, Latvia, Lithuania, Luxembourg, Netherlands, and Poland), Eastern (Slovakia), and Southern Europe (Greece, Malta, Slovenia), and small deposits in Ireland, Hungary and Portugal could limit 30% of removals from ERW.

Barriers to implementing ERW include the logistical challenge of scaling up the supply chain for mineral distribution across diverse EU agricultural lands (Oppon, 2020). Additionally, policy and regulatory uncertainty around land use, environmental consequences at large scale, and carbon accounting may slow development (Clarkson *et al.*, 2024; Spence *et al.*, 2021; Steg *et al.*, 2022). Systems for monitoring ERW are at an early stage and lack long-term field data that would provide confidence to the market (Clarkson *et al.*, 2024). Lastly, there are public acceptance issues, driven by limited awareness and scepticism (Spence *et al.*, 2021). Overcoming these barriers will require integrated policies, targeted subsidies, streamlined regulatory frameworks, and investment in monitoring technologies. Critical to this is a systematic assessment of ERW resources and their deployment patterns to agricultural land.

3.2. Geochemical CDR in Spain

Spain's National Energy and Climate Plan sets out a 23% reduction in greenhouse gas emissions by 2030 (Braga *et al.*, 2022) with a 2050 target of 90% reduction (Sun *et al.*, 2021). Currently Spain's long term climate strategy aims for "natural" removals absorbing the remaining using a combination of reforestation, wetland restoration, and agroforestry (equivalent to 37 $MtCO_2\ yr^{-1}$ by 2050, (Carbon Gap, 2025b).

Spain has approximately 14,800 km^2 of basic and ultrabasic rock near to the surface, with around 1,900 km^2 of exposed material in unprotected areas (Bullock *et al.*, 2023). The latter would equate to approximately 12.7 Gt of material (assuming a 20 m quarry working depth, and a rock density of 3 $t\ m^{-3}$), with a CDR potential of 5 $GtCO_2$. Similar to the UK (Renforth, 2012) this is a resource considerably greater than any realistic future needs of Spain. Similarly, carbonate rock deposits cover approximately 109,500 km^2, and around 773 km^2 that are exposed in unprotected areas. Industrial sector by-products may be able to remove an additional 7.7 $MtCO_2\ yr^{-1}$ (Bullock *et al.*, 2023). gCDR could make a significant contribution to Spain's future CDR requirements.

An exploration of ocean alkalinity deployment scenarios for Spain, Foteinis *et al.*, (in review) take a prospective life-cycle assessment approach for examining 3 technologies (ocean liming (Renforth *et al.*, 2013), coastal enhanced weathering (Meysman and Montserrat, 2017), and electrochemistry (Eisaman, 2024). This case study specifically explores opportunistic use of existing industries and supply chains (*e.g.*, mining, calcination, and desalination) to deploy these technologies, and suggests that a net CDR potential of >9 $MtCO_2$ yr^{-1} is possible by 2030, increasing to >40 $MtCO_2$ yr^{-1} by 2050.

Deployment of ocean alkalinity enhancement in the EU may be constrained by scientific, legal, economic, and societal barriers. One of the foremost scientific challenges is the uncertainty in carbon sequestration efficiency and short- and long-term ecological effects, which complicates regulatory approvals and public support (Oschlies *et al.*, 2023). Furthermore, governance gaps within the EU and internationally, especially in the application of the London Protocol, limit legal clarity on the permissibility and liability of large-scale ocean alkalinity enhancement (Webb *et al.*, 2021). Economically, the high cost and energy intensity of alkaline material production and their distribution limit implementation of some approaches (Eisaman *et al.*, 2023). Furthermore, the lack of standardised monitoring, reporting, and verification protocols creates a lack of confidence in the technologies ability to integrate with climate markets. Low public awareness and stakeholder scepticism toward marine based CDR limit political momentum and investment (Lezaun and Valenzuela, 2024). Overcoming these barriers will require a coordinated EU-wide policy framework, robust pilot studies, and public engagement strategies.

4. CONCLUSION

Geochemical CDR approaches are emerging as promising methods to remove carbon dioxide from the atmosphere. While these approaches have not penetrated mainstream climate policy in the EU, they are beginning to be considered as part of the UKs CDR portfolio. The analysis above suggests that current production of by-product or waste mineral resources in the EU has the potential to remove 274 – 368 $MtCO_2$ yr^{-1}. This potential is distributed between aggregate fines, alkaline wastes (cement kiln dust, slag), and metal mining waste. It also includes what may already be occurring through in-service life carbonation of concrete and lime, and the potential to leverage spare capacity within the cement sector to produce additional alkaline materials. The latter of which would require substantial reduction in emissions at cement production sites for this to be net CDR. Further expansion of rock extraction could add to this capacity, for instance an additional 34-101 $MtCO_2$ yr^{-1} might be contributed through enhanced weathering. These quantities are significant in the context of the expectation that the EU may need to remove 550 $MtCO_2$ yr^{-1} by 2050.

There is considerable asymmetry of resources across the EU. For instance, limited appropriate rock may limit enhanced weathering deployment in Poland, unless resources are transferred from other EU member states. Similarly, the deployment of ocean alkalinity enhancement will only be possible from coastal regions, potentially stranding limestone resources in Central and Eastern Europe unless low-cost, low carbon transportation were used. This asymmetry will influence deployment patterns of specific gCDR technologies and will influence how benefits and burdens are distributed.

The EU urgently requires a systematic evaluation of gCDR resources. There is a wealth of in country knowledge, particularly embedded within national geological surveys, that could be harnessed to provide an inventory of resources. In addition, a systems level analysis would establish the potential pathways for exploiting these materials, and the level of incentives needed to stimulate gCDR commercial projects. Without this, the EU is at risk of creating incentives that promote inefficient use of the resource, and it would certainly be unable to plan for long-term development.

APPENDIX

Table A1

A description of metal mining in which the wastes may be applicable for gCDR

Country	Deposit description*	Grade (%)	CDR Potential** ($kgCO_2\ t^{-1}$)
Bulgaria	Porphyry copper systems consisting of intermediate silicates	0.3-0.4 Cu	194
Finland	Volcanic rock hosted sulphide and ultramafic	1- 3.5 Cu	188 / 417
	Ultramafic hosted	0.00003 PGM	417
Poland	Kupferschiefer ore – carbonate and clay	0.1 – 3 Cu	224
Portugal	Volcanic hosted massive sulphide deposit	2 Cu	188
Romania	Porphyry copper	0.4 Cu	194
Sweden	Porphyry copper + volcanic hosted massive sulphide	0.1 – 1.4 Cu	194 / 188

Notes: *Descriptions of deposits were compiled from https://portergeo.com.au/index.asp - accessed May 2025.
**From those compiled in the supplementary information of (Bullock et al., 2021).

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