No wasted opportunities:

Embedding carbon removal in the management of wastewater, concrete and mine waste

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Content

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The aim of this publication is to formulate evidence-based policy recommendations to accelerate the deployment of CDR technologies in the sectors of wastewater, concrete waste, and mining waste management.

The analysis draws on extensive desk research and direct engagement with leading CDR businesses specialising in wastewater, concrete waste, and mining waste management. The authors gratefully acknowledge the valuable contributions of all external stakeholders and interviewees, whose practical insights and operational expertise have been instrumental in shaping the evidence-based policy recommendations to accelerate CDR technology deployment across Europe.

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Executive summary

The emerging role of carbon dioxide removal (CDR) in climate strategy

To meet global decarbonisation targets and limit the increase of greenhouse gases (GHG) from anthropogenic activities in the atmosphere, governments cannot rely solely on emissions reduction actions. Hard-to-abate emissions from agriculture, aviation, shipping, and industrial processes will remain, requiring complementary strategies[1]. While carbon capture and storage (CCS) and carbon capture and utilisation (CCU) technologies prevent new CO_2 emissions from entering the atmosphere, **carbon dioxide removal (CDR) technologies actively reduce existing atmospheric CO_2 levels.**

DEFINITION

Carbon dioxide removal technologies (CDR) refer to human-led activities that capture CO_2 from the atmosphere and store it durably in geological, terrestrial, or ocean reservoirs, as well as in products. This process includes the intentional enhancement of biological or geochemical sinks and technologies like direct air capture, but it strictly excludes natural CO_2 uptake that occurs without direct human intervention[2].

At the centre of international discussion, the essential role of CDR has been formally recognised. All scenarios in the intergovernmental panel on climate change (IPCC) 6th assessment report demonstrate that CDR is crucial to limiting global warming to 2°C or below by 2100[3]. Nevertheless, there is not yet a cohesive governance structure in place for CDR in the EU. The current legislative framework is fragmented, addressing CDR across several pieces of legislation[4]. Leaving these policy gaps unattended risks the EU failing to deliver CDR at the volumes required by 2040, 2050 and beyond, thereby jeopardising EU-wide, legally binding climate objectives.

This report serves as inspiration when designing a comprehensive CDR policy strategy, by illustrating the status of CDR in three different industries: wastewater treatment, concrete recycling and mine waste management. Their potential for integrating high durability CDR technologies is explored, as well as policy recommendations to tackle existing limitations.

Technologies shaping CDR

CDR technologies are developing at a rapid pace, with each sector pioneering innovative applications tailored to their operational context.

Within wastewater treatment, alkaline materials can be integrated during secondary treatment to sequester biogenic CO_2 released from organic matter decomposition. Moreover, the carbon remaining in sludge enables CDR through various key technologies: (1) biogas production and upgrading, where CO_2 is separated from methane following sludge digestion and subsequently captured and stored; (2) biochar conversion, utilising pyrolysis to transform sludge into highly stable biochar through oxygen-limited thermal decomposition, which can be stored on surface or in geological formations; and (3) CO_2 capture after sludge incineration for permanent storage.

For concrete waste, carbon mineralisation serves as the primary sequestration method, permanently storing CO_2 by chemically binding it within the concrete material. This naturally occurring process can be enhanced, e.g. by processing finely crushed aggregates in reactors, to increase the uptake of CO_2, which also further improves the material properties making it suitable for a broader range of applications.

A comparable carbon mineralisation approach applies to mine tailings. They also can permanently store CO_2 by chemically binding it with the naturally occurring minerals within these mining waste products. This process can either be enhanced on the earth's surface with ambient CO_2 or within reactor systems utilising captured and more concentrated CO_2.

Three industries with significant CDR opportunities

While the total global CDR potential of above-mentioned technologies represents only about 1% of current global emissions, its impact within specific industries could be transformative[5]. In these sectors, the CDR potential meets or even exceeds current GHG output. **This creates a strategic opportunity to design regulatory frameworks that not only scale CDR technologies but transition these sectors toward net-negative profiles.** By achieving a net-negative status, these industries can generate additional "carbon space" necessary to offset emissions in hard-to-abate sectors, particularly those constrained by international competition and high decarbonisation costs. The table below provides an overview of key metrics, based on further analysis, showing the total amount of waste and emissions produced by each sector, as well as their linked theoretical annual CO_2 sequestration potential.

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1 IPCC (2023) Climate change synthesis report – Summary for Policymakers
2 UNEP (2024) Emissions Gap Report 2024
3 IPCC (2024) IPCC AR6 WGIII: CDR Factsheet
4 Carbon Gap (2024) Envisioning a carbon removal strategy for Europe
5 Note: Calculation based on data of the EU Commission, calculations per sector are elaborated on in the respective chapters.

Table 1: Key numbers and metrics per analysed sector.

	Wastewater treatment	Concrete waste recycling	Mining waste management
Amount of waste material annually	**EU:** 40 billion cubic metre [8] **Global:** 380 billion cubic metre [9]	**EU:** 230 Mt [10] **Global:** 1.5 Gt [11]	**Global:** Ni tailings 384 - 621 Mt **Global:** PGM tailings 53 - 89 Mt [12]
Theoretical amount of CO_2 sequestration possible annually	**EU:** 16.6 Mt **Global:** 116 Mt [13]	**EU:** 2.3 Mt – 5.7 Mt **Global:** 7.6 Mt – 18.9 Mt [14]	**Global for Ni and PGM tailings:** 136 Mt - 221 Mt (by 2030)[15]
Sector emissions in CO_2eq	**25.5 Mt** Annual EU emissions from wastewater treatment and discharge (excluding biogenic CO_2)[16].	**2.3 Mt** Total EU emissions generated to process 230 Mt of concrete waste into Recycled Concrete Aggregate (RCA)[17].	**51 Mt** Global emissions from the Nickel production sector[18].

The business case for CDR in these sectors

All three industries demonstrate compelling business cases for CDR technology adoption. Wastewater treatment and concrete waste sectors face minimal external EU competition, positioning them favourably for CDR integration. The mining sector operates in an international market but is positioned as a strategic EU priority due to its criticality for supply chain resilience, also opening the window for building a unique mining industry including CDR technology integration.

This study shows that integrating CDR in the wastewater treatment sector would have a minimal impact on the end consumer price. It was found that adding limestone during wastewater treatment would only increase the total water costs by less than 1%, even without considering the sale of carbon credits, translating to less than €3.00 annually per consumer on average water bills[6].

CDR technology integration in the concrete recycling sector also demonstrated a marginal economic impact: Maximally integrating the CO_2 mineralisation technology in concrete production, would represent far less than 1%[7] of total building project costs. This calculation also did not yet consider carbon credit revenues or the improved aggregate quality as a result of mineralisation, enabling more premium applications.

For the mining waste management sector, larger scale operations of the relevant CDR technologies are still being developed, so a comprehensive cost analysis could not yet be established. However, preliminary analysis shows that the total impact of CDR technology integration on the end-user product prices using the associated mined minerals would also be minimal.

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6 Note: Calculations are further elaborated on in "Deep dive: wastewater liming"
7 Note: Calculations are further elaborated on in "Deep dive: enhanced carbon mineralization of concrete waste"
8 According to WISE, Overview: urban waste water production and its treatment., in the EU, households and certain industries generate the equivalent of 107.68 million m3 wastewater per day.
9 Qadir M et al. (2020) Global and regional potential of wastewater as a water, nutrient and energy source.
10 Note: The total amount of waste in the construction sector is 862 Mt. According to Interreg Europe and Cembureau, at least one third of the total construction and demolition waste is concrete. This mostly aligns with the amount of mineral waste from construction and demolition which is 302 Mt. Source: Eurostat (2025) Generation of waste by waste caregory, hazardounesness and NACE. & Interreg Europe (2022) Collection and recycling of construction and demolititon waste & Cembureau, Circularity & Construction.
11 Note: Own calculation based on data from the World Bank (What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050), assuming 1/3rd of global construction and demolition waste is concrete waste and a recycling rate of 50%.
12 Phil Renforth (2019) The negative emission potential of alkaline materials
13 Note: Calculations are further elaborated on in "Potential scale of CDR in urban WWTPs"
14 Note: Calculations are further elaborated on in "Potential scale of CDR in concrete waste management"
15 Phil Renforth (2019) The negative emission potential of alkaline materials
16 Eurostat (2025) Greenhouse gas emissions by sector
17 Note: Based on the assumption of 10 kg of CO_2(eq) GHG emissions to produce one ton of RCA from construction and demolition waste. To process 230 Mt of concrete waste, this results in 2.3 Mt of GHG emissions. This value is derived from literature (Source: Hosseini, S.A. et al. (2025) Cross-country life cycle assessment of construction and demolition waste recycling with evaluation of energy use, carbon emissions, and regional trade-offs. & Concrete Europe (2016) Closing the loop, what type of concrete re-use is the most sustainable option?)
18 Carbon chain (2024) Understand the emissions intensity of your nickel commodity

Table 2: Technology overview table.

	CDR in wastewater treatment sector			
Technology	**Alkalinity management** (including wastewater liming)	**Sludge conversion into carbon storage**	**Carbon capture during sludge incineration**	**Carbon capture during biogas upgrading**
TRL	6-7	8-9	9	9
Opportunities	• Extra cost saving opportunities linked to optimisation of sludge management and reduced chemical consumption. • Limited cost impact: for a large urban WWTP, cost increase of less than 1% of CAPEX. • Environmental co-benefits linked to alkalinity management.	• Extra potential revenues through the creation of valuable by-products: ◦ Bio-oil ◦ Syngas ◦ Biochar • Environmental co-benefits from biochar application in the agricultural sector (soil fertility and water retention).	• CO_2 capture technology for sludge incineration could also be used for incineration of other wastes. • Energy recovery after incineration can produce electricity for extra revenues.	• The CO_2 is already at a very high concentration after biogas upgrading, lowering the cost to capture it. • Biomethane generated by the upgrading of the biogas can be used for electricity or heating.
	Additional revenue opportunities through the potential generation of carbon credits.			
Challenges	• Additional costs linked to extra CAPEX investments as well as OPEX. The OPEX depends on the close availability of alkalinity materials.	• Additional costs linked to extra CAPEX investments (for the pyrolysis reactor) as well as OPEX (energy requirements). • The CDR potential is also linked to availability of storage sites for the produced biochar.	• Cost linked to energy consumption for carbon capture and high cost of equipment. • Dependence on CO_2 storage locations and CO_2 transport infrastructure.	• Cost linked to energy consumption for carbon capture and high cost of equipment. • Dependence on CO_2 storage locations and CO_2 transport infrastructure.
	Risk-averse & highly regulated sector. Limited financial incentives for CDR uptake. Lack of recognition for decarbonisation efforts due to incomplete CO_2 accounting methodologies.			

TRL 1 – 3: Basic research stage; TRL 4 – 6: Applied research and validation stage; TRL 7 – 9: System development and deployment stage

	CDR in concrete waste management sector	CDR in mining waste management sector
Technology	**Enhanced carbon mineralisation**	**Carbon mineralisation**
TRL	8	4-8
Opportunities	• Potentially increased quality of building materials. • Significant potential to source concrete waste in urban areas, linked to the continuous activity in demolition projects.	• Momentum in EU around the extraction of critical raw materials for the clean technology manufacturing. • Cost saving opportunities through: ◦ Reduced monitoring costs linked to increased mineral stability. ◦ Reduced long-term waste management costs.
	Additional revenue opportunities through the potential generation of carbon credits.	
Challenges	• Availability of low cost and high purity CO_2 is location dependent.	• Sectorial price sensitivity. • Low public acceptance for opening new mines.
	Risk-averse & highly regulated sector. Limited financial incentives for CDR uptake. Lack of recognition for decarbonisation efforts due to incomplete CO_2 accounting methodologies.	

Limitations and policy recommendations

This study thus identifies significant potential for CDR technologies in wastewater treatment, concrete recycling, and mining waste management, but also highlights key barriers to rapid scale-up, including:

- **Knowledge gaps** on GHG emissions and co-benefits hinder accurate assessment and decision-making.
- **Incomplete GHG inventories** fail to fully recognise CDR contributions.
- **Few pilot and first-of-a-kind (FOAK) projects** limit technology validation and cost reduction.
- **Low voluntary willingness to pay premium prices** restricts market demand.
- **Absence of policy mandates** slows deployment, especially in sectors where CO_2 pricing is absent.
- **Limited CO_2 infrastructure** increases costs and complexity.

To overcome these limitations, a two-pronged policy approach is recommended: facilitating measures to mature technologies and embedded CDR policymaking to mandate uptake.

The **facilitating measures** are:

- **Prioritise research** to close knowledge gaps on emissions and co-benefits and build a comprehensive database including life-cycle assessments and techno-economic analyses. This data could feed into existing databases, such as the European Innovation Centre for Industrial Transformation and Emissions (INCITE).
- Provide **dedicated public funding**, such as grants and blended finance, to accelerate pilot and FOAK projects across sectors, enabling technology maturity and scale.
- Improve **GHG monitoring and reporting frameworks**, such as United Nations Framework Convention on Climate Change (UNFCCC) national reporting and the GHG protocol, to fully capture CDR impacts, including biogenic CO_2 and other gases.
- Guarantee the inclusion of these sector-specific CDR technologies in the different **CDR purchasing schemes,** especially the policy-driven schemes, such as the registry that will be established in the European carbon removals and carbon farming (CRCF) regulation.

The **embedded CDR policymaking recommendations** have as a main advantage that they can guarantee a chosen level of CDR technology adoption, even without the need for public subsidies. Embedded CDR policy requirements proposed in this study include mandates, standards and public procurement. This includes:

- For **wastewater treatment**: extend the Urban Wastewater Treatment Directive to require CDR targets alongside the current energy neutrality and GHG emission reporting requirements.
- For **concrete recycling**: adopt a delegated act under the Waste Framework Directive mandating a minimum amount of carbonation when recycling concrete waste. Moreover, implement EU harmonised standards, allowing a maximum amount of carbonated recycled aggregate use in new concrete products. Finally, also public procurement can be used as an effective instrument, stimulating the use of carbonated recycled aggregates in public construction projects.
- For **mining waste management**: revise the Extractive Waste Directive to set GHG emission targets, as well as recognising enhanced mineralisation as Best Available Technique (BAT) as part of the Industrial Emissions Directive (IED).

Abbreviations

AMD: Acid Mine Drainage

BAT: Best Available Technique

BECCS: Bioenergy with Carbon Capture and Storage

Bio-CCS: Bio Carbon Capture and Storage

CBAM: Carbon Border Adjustment Mechanism

CCS: Carbon Capture and Storage

CCU: Carbon Capture and Utilisation

CDR: Carbon Dioxide Removal

CEC: Cation Exchange Capacity

CH_4: Methane

CHP: Combined Heat and Power

CO_2: Carbon Dioxide

C&DW: Construction and Demolition Waste

CRMA: Critical Raw Materials Act

CRM: Critical Raw Materials

CRCF: Carbon Removals and Carbon Farming

DAC: Direct Air Capture

DACCS: Direct Air Carbon Capture and Storage

ERW: Enhanced Rock Weathering

ETS: Emission Trading Scheme

EU: European Union

EPR: Extended Producer Responsibility

FID: Final Investment Decision

FOAK: First-of-a-Kind

GHG: Greenhouse Gas

IED: Industrial Emissions Directive

INCITE: Innovation Centre for Industrial Transformation and Emissions

IPCC: Intergovernmental Panel on Climate Change

LCA: Life Cycle Assessment

LOW: Low-carbon Oxide from Waste

MRV: Measurement, Reporting, and Verification

N_2O: Nitrous Oxide

PFAS: Per- and Polyfluoroalkyl Substances

PGE: Platinum Group Elements

PGM: Platinum Group Metals

RCA: Recycled Concrete Aggregates

REE: Rare Earth Elements

ROC: Reactive Oxide to Carbonate

ROI: Return on Investment

SM: Supplementary Cementitious Materials

TEA: Techno-Economic Evaluations

TRL: Technology Readiness Level

TSF: Tailings Storage Facility

UNFCCC: United Nations Framework Convention on Climate Change

WRRFs: Water and Resource Recovery Facilities

WWTPs: Wastewater Treatment Plants

Units

mg : milligram

kg : kilogram

Mt: Million tonne

Gt : Giga tonne

m^3 : cubic metre

Wt% : Weight percentage

€: Euro

$: Dollar

Introduction

Deploying high-durability carbon dioxide removal (CDR) through industrial waste management sectors

The imperative of CDR

Achieving net zero emissions and stabilising the global climate cannot rely solely on reducing greenhouse gas emissions. While emission cuts are critical, they are not enough to reverse the accumulated carbon dioxide already present in the atmosphere. Carbon Dioxide Removal (CDR) technologies emerge as an indispensable tool to actively extract and securely store billions of tons of CO_2 annually by mid-century[19]. CDR technologies refer to the technologies and human activities that remove and durably store CO_2 from the atmosphere[20].

Although CDR is not a substitute for deep emissions reduction, the absence of CDR at the unprecedented emissions rate caused by anthropogenic activities puts the world at risk of overshooting climate targets, causing irreversible environmental impacts, and undermining long-term sustainability. **In essence, CDR technologies allow a path to not only halt global warming but also to reverse its course[21].**

The critical need for durable, long-term CDR

To truly achieve what is known as durable or geological net zero, it is not enough to simply remove carbon from the atmosphere. We must ensure that this carbon is stored securely over the long term. This means balancing the persistent, hard-to-abate fossil fuel emissions with carbon storage solutions that offer high durability and minimal risk of reversal, making these solutions less reliant on temporary contracts or regulatory frameworks. **To stay on track for mid-century climate goals, it is imperative to rapidly scale these high-durability solutions to hundreds of Mt of CO_2 removal annually by 2030.**

Geological storage, whether deep underground in stable rock formations or through geochemical processes akin to natural mineralisation, can provide this level of permanence, locking away CO_2 for centuries to millennia. Unlike temporary or biologically based methods, these approaches significantly reduce the risk of carbon re-entering the atmosphere, making them indispensable for credible, long-lasting climate mitigation. It is thus important to distinguish between "conventional" and "novel, highly durable" CDR methods to understand their respective roles and reliability in delivering durable climate outcomes.

Industries and waste management sectors with hard-to-abate emissions can truly benefit from high-durability CDR

Certain industries, especially those with hard-to-abate emissions, stand to gain significantly from integrating high-durability CDR solutions into their operations. These sectors face persistent emissions challenges that cannot be fully addressed by conventional mitigation alone, making CDR a vital complement for achieving genuine net zero progress. Waste management, in particular, presents a compelling opportunity for scalable CDR deployment. With vast volumes of residual materials and continuous high-throughput processing, waste streams offer abundant feedstocks and infrastructure capacity for CDR technologies. Leveraging these sectors could not only accelerate CDR scale-up but also create synergies with other industrial processes, unlocking cost-effective pathways to permanent carbon removal.

Financing for high-durability CDR technologies should extend beyond the voluntary carbon market

Voluntary carbon markets have kick-started the deployment of CDR technologies, but cannot be solely relied upon

Initial piloting of higher-durability CDR technologies (e.g., biogenic carbon capture and storage (bio-CCS), direct air carbon capture and storage (DACCS), biochar, carbon mineralisation, etc.) has been made possible mostly through purchases of voluntary carbon credits from private companies with high profits per ton emitted CO_2, mostly in the technology sector[22]. This pool of voluntary demand has been crucial in kickstarting CDR, but it has the risk of rapidly running dry. Several limitations to the voluntary carbon market and specifically voluntary CDR purchasing limit the deployment of CDR technologies.

Therefore, relying solely on the voluntary carbon market presents its limitations and alternative financial methods or measures to support the deployment of CDR technologies should be further investigated.

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[19] Abouelnaga M (2022) Engineered Carbon Dioxide Removal: Scalability and Durability

[20] IPCC, CDR Factsheet

[21] IPCC (2022) Climate Change 2022 Mitigation of Climate Change

[22] Note: Analysis based on CDR.fyi, consulted in 2025, >80% of the purchases are from the technology sector.

Limitations of voluntary CDR purchasing:

- **Dependency on climate conscientiousness** – Corporates and government departments can only commit large budgets to buying CDR when the political winds, and level of public awareness/demand from customers justify large voluntary climate spend.

- **Competing priorities & high cost** – Potential CDR buyers may have a lot of climate and environment-related activities and causes they could support. The high CO_2 cost of high-durability CDR activities is highly visible and can become internally contentious. Marginal abatement cost remains a dominant paradigm in corporate sustainability decision, which could result in high-durability CDR technologies to struggle to retain support.

- **Reliance on compensation claims** – When CDR is purchased as a product, the purchase needs value for money. Almost invariably, this use case is to substantiate a "compensation claim", usually a one-for-one claim of having "neutralised" or "compensated for" specific unabated emissions. Policy or investor schemes, as well as GHG carbon accounting frameworks (i.e. GHG protocol & SBTI), favouring these "compensation claims" can change in time, which could impact the durability of support provided to high-durability CDR technologies.

- **Limited government control/oversight** – The voluntary carbon markets lack a single regulator, limiting the control and oversight of individual governments.

- **Unpredictability** – The unstable nature of voluntary carbon markets makes long-term financing & planning for CDR project developers difficult. This unpredictability also impacts policy makers that are relying on this voluntary market for meeting their climate targets.

Embedded CDR policymaking as a way forward

In theory, any set of rules or specifications governing a product, service, or activity could be modified and adapted to make carbon removal either required or more likely to occur. In the context of heavily regulated industries, this update of existing policies could generate "regulatory demand" for more carbon removal and alternatively could be thought of as "supply-side" CDR policy. We call such an approach embedded CDR policymaking, because the goal is to embed carbon removal directly into the ruleset that industrial actors play by.

Examples of embedded CDR policies include product or environmental standards, sector policy targets and procurement targets, each of them causing negative emissions as an effect of a regulatory change.

Challenges to embedded CDR policymaking may on the other hand include possible conflicts with regulatory rulesets that tend not to be frequently updated. In addition, a key consideration is the allocation of costs and responsibility for financing CDR initiatives. Moreover, reliance on motivations beyond a strict climate-first focus, such as environmental health or service quality, may risk diluting the primary climate objectives. Finally, the deployment of CDR technologies requires at a broader scale a fundamental paradigm change shift, transitioning from traditional metrics based on euros per ton of CO_2 towards evaluating percentage changes in the cost structure of underlying activities.

Identifying embedded CDR policymaking options

CDR is not a monolith, the wide variety of CDR methods and contexts in which they can be deployed means embedded CDR policymaking may only be advantageous under the following conditions:

Rule takers – Industries or sectors that are heavily-regulated and accustomed to delivering products or services against a tightly constrained specification are strong candidates for embedded CDR policymaking. Examples include waste management, food manufacturing and public works construction which may be accustomed to adapting to changing environmental, health, safety, and quality standards.

Localised markets – When an activity has to be performed in specific areas and/or only with specific actors, such as many forms of waste management (wastewater treatment, municipal solid waste incineration, concrete recycling, etc.), and has localised pricing, i.e. low exposure to international commodities markets (e.g., wastewater is managed locally and cannot be outsourced/off-shored), the associated product or service end-price can be increased related to mandated CDR technology adoption without being subject to international competitors.

Strong non-climate motivations – When activities are driven by non-climate goals (such as environmental or political mandates) and have the bonus of removing carbon, significant volumes of negative emissions could be generated through such regulatory specifications. By integrating CDR as a secondary function, regulations can address sector-specific challenges while simultaneously generating significant negative emissions. For example, government-mandated and funded river liming in parts of Scandinavia have been conducted to reduce river system acidification and improve fisheries health, while also resulting in the uptake of CO_2 emissions[23]. Conversely, carbon removal activities that solely deliver a climate benefit (e.g. Direct Air Capture (DAC) with deep-sea CO_2 storage) will be less of a fit for embedded CDR policymaking and will likely continue to be driven by markets and policies focused on neutralising hard-to-abate emissions.

Distributed, low-visibility payment absorption – When the additional cost of CDR technologies can be spread across the total service price, and the price increase remains very small that end-users are unlikely to notice any difference, it can be easily absorbed by the different involved actors. This can provide a reliable continuous funding stream for CDR projects, especially in essential services such as water treatment, construction waste management and mining.

Lay out and report structure

Based on the previously identified criteria and analysis of different sectors' potential for embedded CDR policymaking, we ultimately selected three sectors for further analysis in this study: wastewater treatment; concrete waste recycling and mining waste management. The following chapters explore each sector's potential for high-durability CDR technologies and embedded CDR policymaking. They are structured as follows.

First, an overview of each sector's core processes and associated sources of GHG emissions emitted from those activities is given. Then, the opportunity for CDR within that specific sector is detailed including an overview of the different available CDR technologies, the CDR potential, an economic assessment and an illustration of concrete examples.

Finally, a wide range of policy recommendations aimed at the deployment at scale of CDR technologies within the chosen sectors are provided, preceded by a summary of key limitations. Policy recommendations are divided in two distinct parts. On the one hand, facilitating measures are presented, that can help to make CDR technologies more mature or contribute to the business case for deploying CDR technologies. On the other hand, embedded CDR policy recommendations are presented, sector tailored, that can guarantee the scale up of CDR technologies, by mandating a minimum uptake of CDR technologies, either via policies, standards or public procurement.

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[23] UIA (2020) Encyclopedia of world problems and human potential

Carbon dioxide removal opportunities in the wastewater management sector

The wastewater treatment sector and its processes

Municipal as well as some pre-treated industrial wastewater streams are systematically collected and directed to urban treatment facilities, where substances harmful to the environment and public health are either eliminated or mitigated to levels deemed acceptable under regulatory standards, before the treated water is discharged into nature[24].

In the EU, approximately 30,000 urban wastewater treatment plants (WWTPs)[25] are responsible for the collection, treatment[26], and discharge in natural water bodies of almost all (97%) of the 40 billion m^3 of wastewater produced by households, commercial buildings and small industries each year, equivalent to around 400 billion bathtubs[27; 28].

In a conventional wastewater treatment plant, after large solids and grit are removed through screening and sedimentation (primary treatment), a biological treatment (secondary treatment) is generally used to break down organic pollutants and excessive nutrient loads (such as nitrogenous compounds, which may cause eutrophication in water bodies). In the biological tank, a mixture of microbes (sludge) metabolizes the pollutants most commonly under oxygen-rich (aerobic) conditions, but also oxygen-free (anaerobic) settings in specific contexts (i.e. high organic loads).

The sludge undergoes cyclical processes of settling and recirculation, in which a portion of the settled sludge is returned to the biological tank (also called aeration tank) to sustain an effective microbial population, while the excess is dewatered and either repurposed (i.e. for agriculture or anaerobically digested for biogas production, a renewable energy source primarily composed of methane) or disposed of in landfills.

After the main biological process, a tertiary treatment is normally needed to further purify the treated water by removing residual nutrients or organics, microorganisms leaked from the biological treatment or fine solids, through filtration, disinfection (e.g. chlorination, UV irradiation or ozonation), or chemical processes (e.g. precipitation). WWTPs increasingly add a quaternary treatment phase to the treatment process to remove additional micropollutants such as pharmaceuticals, pesticides and microplastics.

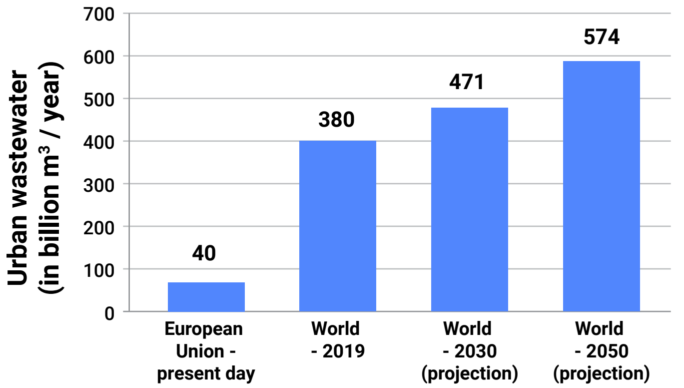

Figure 1: Annual urban wastewater production in Europe and in the world, including projections towards 2050.[29]

Greenhouse gas emissions produced by wastewater treatment

If the primary focus of WWTPs has historically been their effectiveness in removing pollutants, recent years have seen growing attention on their environmental impact, mostly for their contribution to greenhouse gas (GHG) emissions. The precise quantification of GHG emissions in national or corporate inventories still requires further investigation, since most inventories focus only on CH_4[30] and N_2O[31] emissions produced in WWTPs and do not include any fossil or biogenic CO_2 emissions. Next to including all the different type of GHG emissions in inventories, also more research is needed to fully understand the different GHG emissions produced from the various types of WWTPs (see policy recommendations later in this chapter).

Below we describe the different types of GHG emissions that are linked to the various WWTP processes, and the current most established accounting practices. A link is made with the different amounts of GHG emissions that are produced in WWTP, based on recent research that assembled a comprehensive GHG inventory of 15,863 facilities in the USA[32].

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[24] Official Journal of the European Union (2024) Directive (EU) 2024/3019 of the European Parliament and of the Council of 27 November 2024 concerning urban wastewater treatment (recast)

[25] EU Commission, Urban Wastewater

[26] Note: According to the EU regulatory framework, wastewater flows generated in urban areas with over 10 000 people (68% of all wastewater flows) need to be biologically treated with nitrogen and/or phosphorus removal before being discharged.

[27] According to WISE, Overview: urban waste water production and its treatment, in the EU, households and certain industries generate the equivalent of 107.68 million m^3 wastewater per day.

[28] Note: While some (usually small) industries can discharge into public sewers, larger industrial plants mostly treat their wastewater onsite or in specific industrial wastewater plants.

[29] Qadir M et al. (2020) Global and regional potential of wastewater as a water, nutrient and energy source.

[30] Note: According to the sixth assessment report of IPCC, methane (CH_4) has a GWP that is 27-30 higher compared to CO_2 on a 100-year time horizon

[31] Note: According to the sixth assessment report of IPCC, nitrous oxide (N_2O) has a GWP that is 273 higher compared to CO_2 on a 100-year time horizon

[32] Abbadi et al., (2025) Benchmarking greenhouse gas emissions from US wastewater treatment for targeted reduction

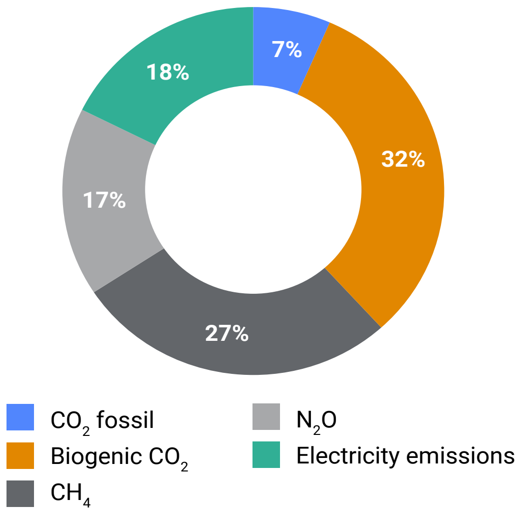
Direct GHG emissions

The biogenic CO_2 emissions that can result in CDR are a significant part of the total direct GHG emissions of WWTP. They account for 39% of the total direct emissions (including fossil CO_2, biogenic CO_2, N_2O and CH_4).

During both the secondary treatment and the sludge treatment, organic material is converted in CO_2. While most of this CO_2 is considered biogenic and therefore not accounted for in scope 1 emissions of GHG inventories, some research indicates that >10% of the total organic carbon in municipal wastewater can be of fossil origin[33]. Moreover, direct fossil CO_2 emissions can also be produced from fossil fuel reliant machinery in the WWTP or when fossil fuels are incinerated in the WWTP for energy provision.[34]

Concurrently, nitrous oxide (N_2O) is generated as a byproduct of biological nitrogen removal processes, in which ammonia (NH_3) is oxidized to nitrate (NO_3^-) in presence of oxygen (nitrification process) followed by nitrate reduction into harmless nitrogen gas (N_2) under anoxic conditions (denitrification process). N_2O emission (which account for ~21% of the direct emissions in CO_2 equivalent[33]) is particularly favoured if nitrogen removal processes operate under suboptimal conditions, such as low dissolved oxygen during nitrification or insufficient carbon availability during denitrification, which hinder the complete conversion to N_2 and lead to the accumulation and release of unreacted N_2O. In addition, methane (CH_4) is also released during the biological process emissions (accounting for ~33% of the direct emissions).[33] A major contributor to CH_4 emissions is anaerobic digestion, where the produced CH_4 can escape into the atmosphere as fugitive emissions if it is not fully captured and used as an energy source.

GHG emissions per m^3 of treated wastewater (Total GHG emissions*: ~0,33 - 1,8 kg CO_2eq / m^3)



*depending on the treatment plant, its processes and the location

Figure 2: Visual representation of total GHG emissions generated in WWTPs (Scope 1 & 2) [34]

Indirect Emissions

Indirect emissions primarily arise from the energy supply required for the plant operations (mainly electricity for aeration, pumping stations, etc.) and the transport and consumption of chemicals. Furthermore, the construction and renovation of both the sewer system and the WWTP infrastructure itself also add to the overall GHG footprint. Emissions related to electricity consumption can amount up to 22% of total direct emissions, but are largely dependent on the electricity sources that are used.

Carbon accounting of these emission streams

Carbon accounting for WWTPs follows established methodologies from frameworks like the GHG Protocol (for corporate reporting) and United Nations Framework Convention on Climate Change (UNFCCC) (for national reporting). These systems categorize emissions to provide a clear and comprehensive GHG footprint.

The UNFCCC utilizes the Intergovernmental panel on climate change (IPCC) guidelines to establish accounting rules for emissions from wastewater treatment and discharge. These guidelines concentrate primarily on potent greenhouse gases like CH_4 and N_2O. Because the CO_2 released during both the treatment process and the incineration of sludge[35] originates mostly from the breakdown of organic matter, it is classified as biogenic and is consequently not included in the official emissions accounting[36]. Hence any CDR opportunities in these processes are not reflected either. In the categories of 'industrial process and product use' and 'fuel combustion' the capture of biogenic CO_2 can be acknowledged, specifically mentioning its reflection in negative emissions[37], whereas this is not mentioned in the wastewater treatment and waste incineration categories. Therefore, it is unlikely that any CDR coupled to the wastewater treatment process or incineration of sludge can be reflected in the UNFCCC reporting framework.

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[33] Abbadi et al., (2025), Benchmarking greenhouse gas emissions from US wastewater treatment for targeted reduction

[34] Note: Created based on data retrieved from: Abbadi et al., (2025), Benchmarking greenhouse gas emissions from US wastewater treatment for targeted reduction

[35] Note: Research suggests that wastewater contains an appreciable amount of fossil organic carbon. The IPCC will improve future guidelines to estimate such non-biogenic emissions.

[36] IPCC (2019) 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories – Incineration and open burning of waste – Wastewater treatment and discharge

[37] United Nations (2021) Common reporting tables on National Inventory Reports

Within the GHG Protocol for corporates, initial guidelines exist, whereas it is acknowledged that the sector specific guidelines for the waste sector are to be developed. Direct emissions of methane (CH_4) and nitrous oxide (N_2O), which primarily originate from the decomposition of organic matter and nitrification/denitrification processes, are categorized and reported under Scope 1. Indirect emissions stemming from electricity consumption (Scope 2), as well as the transport of chemicals and the construction/renovation of infrastructure (Scope 3), are fully integrated into their respective scope totals[38]. Biogenic CO_2 emissions (e.g. stemming from the combustion of sludge) require a separate disclosure, rather than being included in Scope 1[39]. Any CDR initiatives in WWTPs (e.g., biological GHG sequestration) are thus reflected in this separate disclosure[40].

It must be noted however that the GHG protocol is currently developing its "Land Sector and Removals Guidance" which provides companies with detailed rules for measuring and reporting GHG emissions and removals in GHG inventories specifically associated with, among other techniques, carbon dioxide removal technologies[41]. In the current draft, accounting requirements state that reporting removals is optional, and that companies need to separately account for removals based on their sink process (i.e. technological or biogenic sinks) and storage pool (i.e. land based storage, product storage, or geologic storage). Furthermore, the draft outlines specific requirements for GHG removals accounting such as: ongoing storage monitoring or traceability.

Building on these frameworks, the Science Based Targets initiative (SBTi)[42] allows companies to voluntarily validate near-term (5–10 year) and long-term targets, requiring often a reduction of 90 - 95% of scope 1, 2 and 3 GHG emissions by 2050. As specific sectoral guidance is not yet available for waste and wastewater management, organisations in this field utilize the GHG Protocol as their primary tool for setting their SBTI targets.

The opportunity for CDR in WWTPs

One of the most cost-effective strategies to reduce GHG emissions in WWTPs is to adjust the operating conditions of the treatment units[43]. For instance, modifying the organic carbon input can enhance denitrification efficiency while minimising excess carbon oxidation to carbon dioxide. Similarly, optimizing aeration could help to maintain stable oxygen levels during nitrification, thereby reducing N_2O emissions. However, the potential for such adjustments is often limited by the design and technical constraints of existing infrastructure. This highlights the strong need for efficient, non-invasive and low-cost approaches for the minimisation of GHG emissions in WWTPs, including avenues for the removal of GHG. This report highlights several CDR opportunities through alkalinity management and the management of sludge.

CDR through alkalinity enhancement

During the secondary treatment step, the decomposition of organic matter releases biogenic CO_2. Alkaline materials (such as limestone) can react with the released biogenic CO_2 to form stable dissolved bicarbonates. When the treated water effluents are then discharged into the water bodies, the bicarbonates released in nature remain long-term storage for biogenic CO_2 generated in WWTPs, effectively reducing biogenic CO_2 emissions in the WWTP. In addition, this technique can also be used to increase the alkalinity of the wastewater, where the use of natural alkaline materials as limestone have the additional benefit of avoiding large pH variations.

Other relevant CDR techniques in the broader water management sector

There are several other CDR techniques being explored within the broader water management sector. These methods extend beyond traditional wastewater treatment to include processes like precipitating solid carbonates out of water using lime, which allows for the absorption of more atmospheric CO_2 by the treated water (e.g., CarbonBlue). Another approach involves increasing the pH of rivers through the addition of alkaline materials, enhancing the water's capacity to draw down atmospheric CO_2 (e.g., CarbonRun). Furthermore, electrochemical processes are being developed to directly extract dissolved inorganic carbon from seawater, converting it into CO_2 for storage and returning carbon-depleted water to the ocean to absorb more atmospheric CO_2 (e.g., Captura). Although these CDR techniques warrant dedicated attention, they are beyond the scope of this paper.

CDR in sludge management

Wastewater sludge is a byproduct of the treatment process that is rich in organic carbon. This sludge can be repurposed in various ways: as fertilizer in agriculture and/or to produce energy. The production of energy can be achieved by anaerobic digestion, where the sludge is broken down by microorganisms to produce biogas, or by incineration to produce steam for heat and/or electricity. Landfilling of

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[38] GHG Protocol (2015) Corporate standard & guidance on Scope 2 and 3 emissions

[39] Note: Some uncertainties still exist on whether CO_2 emissions coming from the biodegradation of biomass still needs to be reported on separately. GHG Protocol: Corporate Value Chain (Scope 3) Accounting and Reporting Standard

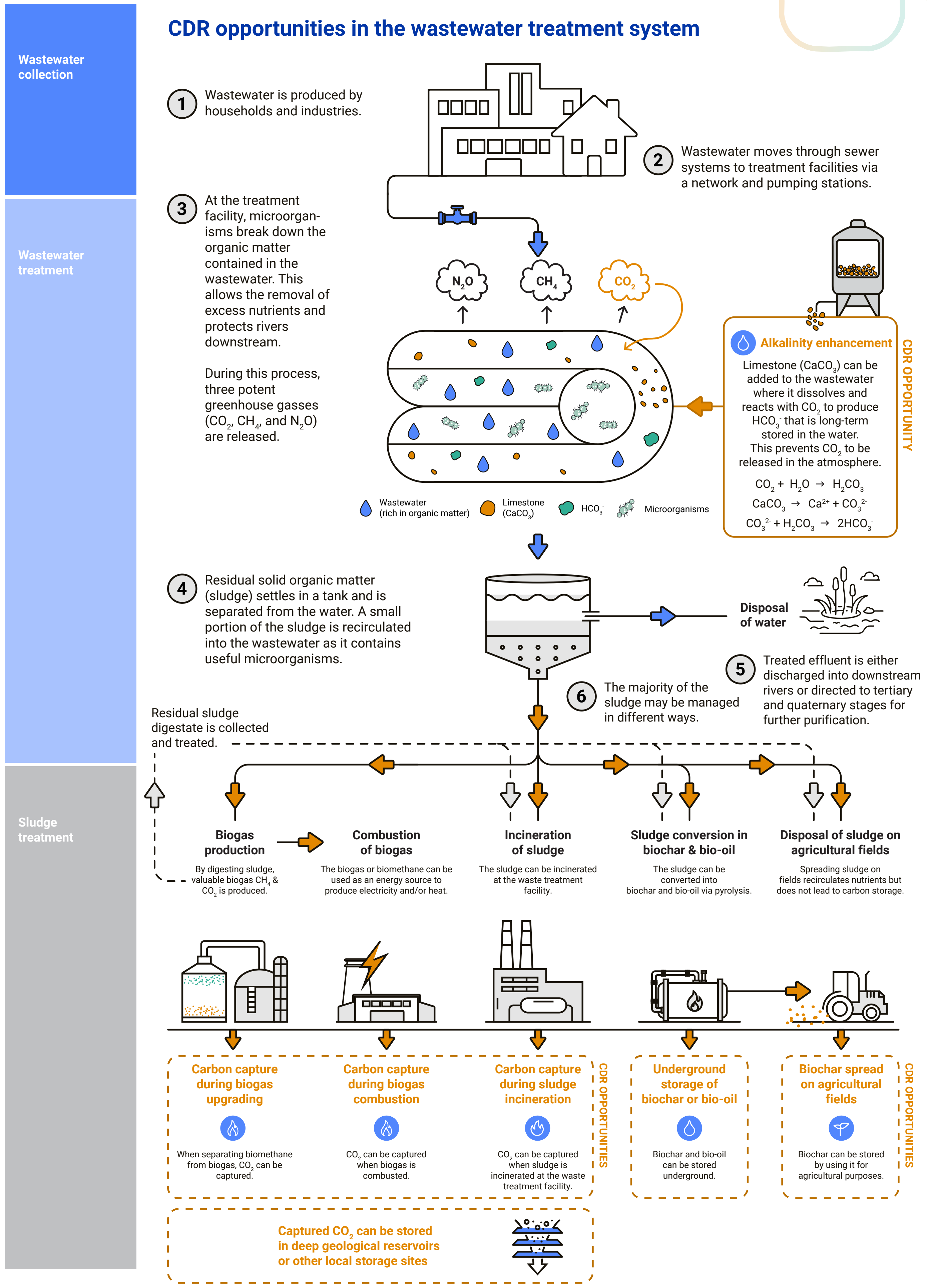
[40] GHG Protocol (2011) Corporate Value Chain (Scope 3) Accounting and Reporting Standard

[41] GHG Protocol (2025) Land Sector and Removals Guidance

[42] Science based targets

[43] Campos J.L. et al (2016), Methyl Complexes of the Transition Metals

CDR opportunities in the wastewater treatment system



1 Wastewater is produced by households and industries.

2 Wastewater moves through sewer systems to treatment facilities via a network and pumping stations.

3 At the treatment facility, microorganisms break down the organic matter contained in the wastewater. This allows the removal of excess nutrients and protects rivers downstream.

During this process, three potent greenhouse gasses (CO_2, CH_4, and N_2O) are released.

Alkalinity enhancement

Limestone ($CaCO_3$) can be added to the wastewater where it dissolves and reacts with CO_2 to produce HCO_3^- that is long-term stored in the water. This prevents CO_2 to be released in the atmosphere.

$CO_2 + H_2O \rightarrow H_2CO_3$

$CaCO_3 \rightarrow Ca^{2+} + CO_3^{2-}$

$CO_3^{2-} + H_2CO_3 \rightarrow 2HCO_3^-$

4 Residual solid organic matter (sludge) settles in a tank and is separated from the water. A small portion of the sludge is recirculated into the wastewater as it contains useful microorganisms.

5 Treated effluent is either discharged into downstream rivers or directed to tertiary and quaternary stages for further purification.

6 The majority of the sludge may be managed in different ways.

Residual sludge digestate is collected and treated.

Biogas production
By digesting sludge, valuable biogas CH_4 & CO_2 is produced.

Combustion of biogas
The biogas or biomethane can be used as an energy source to produce electricity and/or heat.

Incineration of sludge
The sludge can be incinerated at the waste treatment facility.

Sludge conversion in biochar & bio-oil
The sludge can be converted into biochar and bio-oil via pyrolysis.

Disposal of sludge on agricultural fields
Spreading sludge on fields recirculates nutrients but does not lead to carbon storage.

Carbon capture during biogas upgrading
When separating biomethane from biogas, CO_2 can be captured.

Carbon capture during biogas combustion
CO_2 can be captured when biogas is combusted.

Carbon capture during sludge incineration
CO_2 can be captured when sludge is incinerated at the waste treatment facility.

Underground storage of biochar or bio-oil
Biochar and bio-oil can be stored underground.

Biochar spread on agricultural fields
Biochar can be stored by using it for agricultural purposes.

Captured CO_2 can be stored in deep geological reservoirs or other local storage sites

Figure 3: CDR opportunities in the wastewater treatment system.

sludge should be prevented, as, in addition to (biogenic) CO_2, landfilling also produces methane (CH_4), a strong potent greenhouse gas.

In the different applications below, there is a lot of potential for achieving CDR.

Agricultural use

A traditional disposal method involves spreading treated sludge on agricultural fields as a soil amendment and fertilizer. While this practice recycles nutrients and can initially increase soil organic carbon, it generally does not achieve long-term carbon storage, as the organic matter is susceptible to microbial decomposition, releasing CO_2 and N_2O into the atmosphere over relatively short timescales[44]. Due to its heavy metal and pathogen content, applying sewage sludge to land is increasingly viewed as an unsafe disposal option that could compromise soil quality and present a safety risk[45].

Sludge conversion into biogas

A second sludge management method is the conversion of excess sludge into biogas. Here, the sludge is digested anaerobically to create CH_4 and CO_2[46]. This biogas can be upgraded into pure biomethane, that can be used as substitute for natural gas in the gas grids. During this process, CO_2 is stripped from the methane, which can also be captured and stored, resulting in CDR[47]. After combustion of the biogas or biomethane for energy purposes, the produced CO_2 can also be captured and stored, resulting in additional CDR.

Sludge conversion into carbon storage

To achieve effective CDR from sludge, several other conversion technologies are being explored. Pyrolysis can convert sludge into biochar, a highly stable form of carbon, through thermal decomposition in oxygen-limited environments[48]. Biochar, produced from sludge, can contain 35-40% fixed carbon and, when incorporated into soil, can sequester carbon for hundreds to thousands of years by resisting microbial degradation[49]. This surface storage of biochar in agricultural soils offers co-benefits such as improved soil fertility and water retention[50,51]. While this CDR methodology shows significant promise, its Measurement, Reporting, and Verification (MRV) protocols currently face ongoing debate across the EU.

Alternatively, underground storage of biochar in dedicated geological formations is also a promising pathway for enhanced permanence. Beyond solid carbon, underground storage of raw biomass or bio-oil derived from sludge pyrolysis or hydrothermal liquefaction is another emerging negative emissions technology. Bio-oil, a carbon-rich liquid, can be injected into deep geological formations where it solidifies, effectively locking away carbon[52;53].

Incineration of sludge

Lastly, sludge can also be incinerated. This can be either mono-incineration or combined with other sources. During incineration, energy can be generated, and CO_2 is released. Carbon capture technologies can prevent these emissions from reaching the atmosphere. This involves capturing the CO_2 from the flue gas and then storing it to obtain CDR.

Potential scale of CDR in urban WWTPs

On the EU level, it is estimated that the total amount of biogenic CO_2 released into the atmosphere from the breakdown of organic matter present in urban wastewater, amounts up to ~20.5 Mt per year[54]. Given that the current recorded emissions (excluding biogenic CO_2 emissions) of the treatment and discharge of wastewater are around 25.5 Mt[55], this is a significant number.

The EU's urban WWTPs currently collect 81% of the urban wastewater required for collection under EU regulations[56]. **This makes the theoretical potential for CDR in EU urban WWTPs 16.6 Mt of CO_2 per year, which can offset approx. 65% of all GHG emissions (mainly N_2O and CH_4) currently reported for wastewater treatment in the EU**[57]. Global biogenic CO_2 emissions linked to the treatment of urban wastewater are on the order of ~200 Mt CO_2

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[44] Layla Lambiasi, et al. (2024) Greenhouse gas emissions from sanitations and wastewater management systems: a review
[45] Mian Hu et al. (2021) Thermochemical conversion of sewage sludge for energy and resource recovery: technical challenges and prospects
[46] Cambi (2025) Biogas from Wastewater: A Sustainable Energy Solution
[47] Mahmoud M et al. (2024) Enhancing carbon capture efficiency in biogas upgrading: A comprehensive review on adsorbents and adsorption isotherms
[48] 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
[49] Greenchar climate solutions (2025) Turning Sludge into Carbon Credits: The Biochar Opportunity for Wastewater Treatment Plants
[50] Shahbaz Khan et al. (2024) Biochar Production and Characteristics, Its Impacts on Soil Health, Crop Production, and Yield Enhancement: A Review
[51] Note: An example of a company in this field is AquaGreen.
[52] Isometric (2023) New protocol for Bio-oil geological storage
[53] Note: A player in this field is NULIFE, focusing on the creation of bio-oil. Companies like Vaulted Deep are actively pursuing the deep well injection of organic waste, including biosolids, to achieve durable carbon dioxide removal with a reported durability of over 1,000 years. Source: Nulife, Our technology & Vaulted deep, Putting waste to work.
[54] Note: An average of 140 mg of organic carbon/L of wastewater (Source: Brian H Kiepper et al. (2022) Understanding Laboratory Wastewater Tests: I. Organics (BOD, COD, TOC, O&G) and a conversion factor of 3,67 based on the mole mass of CO_2/mole mass C were used to account for the potential amount of CO_2 emissions from wastewater (Source: Eurofins, How do you calculate how much CO_2 is captured in organic matter ?). These conversion factors were used on the approximately 40 billion m^3 of wastewater produced by households, commercial buildings and small industries each year in the EU (Source: Wise freshwater (unknown) Overview: urban waste water production and its treatment).
[55] Eurostat (2025) Greenhouse gas emissions by sector
[56] Note: According to the EU regulatory framework, approximately 97% of wastewater flows generated in the EU needs to be biologically treated by WWTP, with the remaining 3% treated in alternative wastewater treatment systems (e.g; domestic treatment plants or septic tanks) or directly released in the environment. For more information, see here.
[57] The UNFCCC inventory data reports 23.39 MT of CO_2(eq) emissions for the European Union in 2021, of which 17.15 MT is related to CH_4 and 6.24 MT to N_2O (Source: United Nations, Greenhouse Gas Inventory Data - Detailed data by Party)).

per year[58]. However, with 58% of urban wastewater currently being treated in WWTPs before being discharged to the environment[59], the theoretical CDR potential of WWTPs at the global level is then currently ~116 Mt of CO_2 per year.

The treatment of industrial wastewaters: The treatment of industrial wastewaters, such as those from food, beverage, and paper production, also produces vast amounts of biogenic CO_2. Although the water volumes and CO_2 concentrations of these industrial wastewaters vary by industry, any alkalinity enhancement or sludge management practice that results in the capture and storage of biogenic CO_2 presents a significant opportunity for additional CDR. Expanding the CDR approaches to industrial wastewater streams containing biogenic CO_2 likely offers additional CDR capacity of a similar order of magnitude to that of urban wastewater[60]. Although the potential scale of CDR in industrial WWTPs warrant dedicated attention, estimating the precise theoretical potential CDR opportunity is challenging with the currently available data[61] and is therefore **beyond the scope of this paper**.

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[58] Note: An average of 140 mg of organic carbon/L of wastewater (Source: University of Georgia) and a conversion factor of 3,67 based on the mole mass of CO_2/mole mass C were used to account for the potential amount of CO_2 emissions from wastewater (Source: Eurofins). These conversion factors were used on the approximately 380 billion m3 of wastewater produced globally (Source: Global and regional potential of wastewater as a water, nutrient and energy source, Qadir et al)

[59] Statista (2025) Proportion of domestic wastewater flow safely treated worldwide in 2022 ; United nations (unknown) Progress on Wastewater Treatment (SDG target 6.3)

[60] Source: Rocky Mountain Institute

[61] Note: The exact capacity in these industries is difficult to evaluate, as biogenic carbon emissions in wastewater flows are not typically measured as part of emissions reduction efforts. IPCC regulations do not count these CO_2 releases as emissions because, as biogenic carbon sources, they stem from within the fast carbon cycle, rather than additional emissions from the combustion of fossil fuels. This means emission data from these industries does not contain the biogenic CO_2 from these industries which could be used for biogenic CDR.

Deep dive: wastewater liming

The integration of limestone into wastewater treatment plants is a process designed to enhance alkalinity, aid in flocculation, and achieve CDR. The technology involves the controlled dosing of fine-grained limestone into the secondary treatment step of the wastewater stream.

Process design

This process leverages the natural properties of calcium carbonate ($CaCO_3$) to react with carbonic acid (H_2CO_3) present in the water, which is formed from the produced biogenic carbon dioxide (CO_2) during organic matter breakdown. Adding limestone thus prevents a significant share of the biogenic CO_2 to be released in the atmosphere, by storing it in stable bicarbonates (HCO_3^-). **By doing this, it also maintains a stable and more alkaline pH in the wastewater, preventing any acidity issues that could reduce the efficiency of the process.**

$$CO_2 + H_2O \rightarrow H_2CO_3$$

$$CaCO_3 \rightarrow Ca^{2+} + CO_3^{2-}$$

$$CO_3^{2-} + H_2CO_3 \rightarrow 2HCO_3^-$$

Adding limestone not only helps to manage the water chemistry but also creates a more favourable environment for the binding of micro-flocs, due to the increased concentration of Ca^{2+}, improving the overall settling of sludge.

The dosage of limestone is carefully controlled to optimize these effects, with instrumentation, such as alkalinity analysers, used to monitor and adjust the process in real-time.

Economic perspectives

Capital investment

The capital expenditures (CAPEX) for implementing this technology are primarily driven by the scale of the project, typically ranging from **€0.2 million to €2 million**. For a large urban wastewater treatment plant this is equal to an increase in less than 1% for its CAPEX[63]. The main investments required for retrofitting a WWTP for limestone dosing include:

- **Dosing setup**: This is a readily available, off-the-shelf system that usually consists of a silo for storing the limestone and a screw feeder for precise dosing. For some facilities, a high-solids liquid slurry (75% concentration) can be used, which is shipped pre-mixed in a container and eliminates the need for on-site mixing equipment.
- **Additional analysis and instrumentation**: To ensure effective monitoring and process optimisation, an investment in enhanced

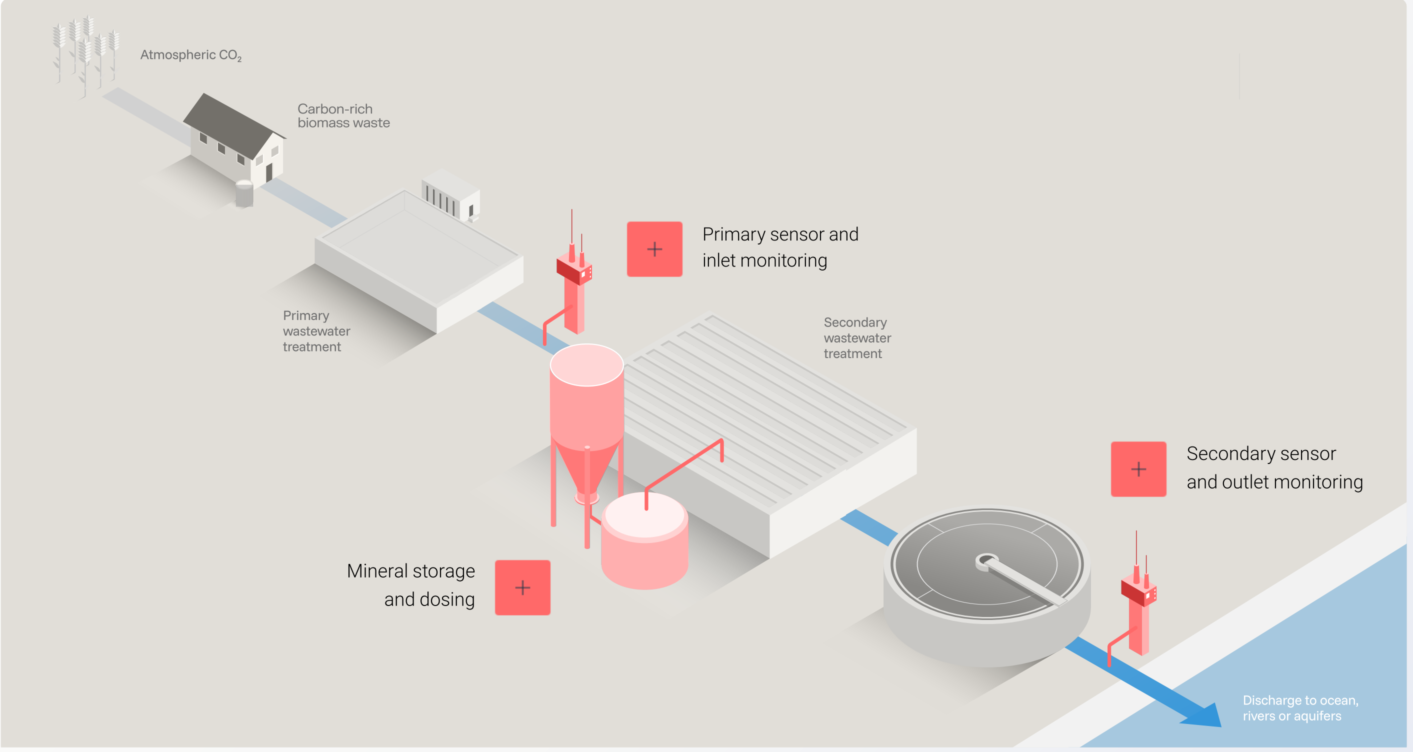

Figure 4: Position of Crew Carbon's operations within the process of wastewater treatment[62]

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[62] CREW Carbon, The win-win the world needs

[63] Hella Water (2025) Understanding the cost of building a sewage treatment plant.

instrumentation is necessary. This includes equipment like alkalinity analysers at the outlet of the treatment process to accurately measure the carbon removal and provide data for modelling improvements.

Operational expenses

The operational expenditures (OPEX) associated with this technology are mainly influenced by the cost of the limestone itself, its transportation, and the energy required for dosing. The operational costs of wastewater liming are mainly determined by the following key factors:

- **Cost of limestone:** The cost of limestone is in the range of €50 - 100 per tonne (incl. transport), depending on the specific characteristics of the material. Specifically, limestone with a finer grain size (smaller than 400 mesh) and higher calcium content (>90%) is optimal for faster dissolution and carbon removal.
- **Cost of transporting limestone**: The transportation cost of limestone to the WWTP needs to be closely monitored. However, while local sourcing of limestone should be prioritised, the use of low-cost and efficient transport methods, such as rail or barges, rather than trucks, can reduce the cost of the raw material delivered.
- **Dosing Costs:** The operational costs for the dosing equipment are generally negligible. These mainly involve the electricity consumption of the screw feeder and the monitoring instrumentation.
- **Maintenance and labor:** Regular maintenance of complex equipment and the labor required to operate the facility are continuous costs.

Impact on water treatment costs

Based on an initial treatment cost of €0.77 per cubic metre, the material cost linked to adding limestone for CDR would result in an estimated cost increase of 4.34% (without considering CAPEX, see table below for the detailed cost estimation). This corresponds to a 0.74% increase in the total cost of water when accounting for freshwater production, distribution, and wastewater collection, transport, and treatment[64]. **On an average water bill of a consumer, this would account for less than €3.00 each year.** This makes the cost of removing one ton of CO_2 currently ranging from €200 to €400, which is in line with the average cost related to bioenergy with carbon capture and storage (BECCS)[65]. This value does not yet consider the sale of carbon credits and will also be lower if a lower quantity of CDR is targeted.

Other potential operational cost savings

The implementation of limestone dosing could also result in other notable savings in a wastewater treatment plant's operational budget, which can partially or fully offset the costs mentioned above. These aspects were not yet considered in the cost analysis above. These savings include:

- **Reduced aeration costs:** By promoting the breakdown of organic matter and managing alkalinity, the technology could potentially reduce the need for aeration in plants where aeration is increased to prevent acidity issues. This results in a potential decrease of energy expenses.
- **Improved sludge management:** The enhanced flocculation improves sludge settling, which can decrease processing and disposal costs.
- **Reduced chemical consumption:** The use of limestone can lessen or eliminate the need for other synthetic chemicals, such as caustic soda or quicklime, which are typically used for alkalinity management, but also flocculation agents.
- **Carbon credits:** The removal of biogenic GHGs through wastewater liming can qualify for the generation of carbon credits that can be traded on voluntary markets, and potentially future compliance markets. Selling these credits represents a significant potential revenue stream that directly monetizes the environmental benefit of the process, thus further offsetting operational costs and improving the overall economic viability of the technology.

Table 3: Estimation of the key parameters and associated costs for a wastewater liming project aimed at carbon dioxide (CO_2) removal.[66]

Average of total organic carbon in wastewater	**140**	*mg of organic carbon per liter*
Conversion of carbon in CO_2	**3.67**	*Mole mass CO_2/mole mass C*
Non optimized cost of limestone	**100**	*EUR/ton*
Amount of limestone used to treat one kg of CO_2	**3.250**	*kg $CaCO_3$/Kg CO_2*
Potential amount of CO_2 released from organic carbon in treated wastewater	**0.514**	*Kg of CO_2 per m^3*
Estimated CO_2 capture rate for liming project	**20%**	*/*
Amount of limestone needed to treat one m^3 of wastewater	**0.33**	*Kg of $CaCO_3$ per m^3 of wastewater*
Estimated cost of limestone per m^3 of wastewater	**0.033**	**EUR/m^3 of wastewater**
Estimated cost per ton of CO_2 removed	**325**	**EUR/ton CO_2**

*Decrease in energy and chemical consumption due to alkalinity management and decrease in sludge disposal costs are not included in the calculation above.

Pioneer projects

The municipal WWTP AVZ[67], located near Freiburg, serves as a pioneering example of this technology. Operating since 1966, the plant processes wastewater for a population equivalent of 660,000, with an annual throughput of approximately 48.18 billion litres. Over the past decade, AVZ has been using limestone from Omya primarily to manage alkalinity and aid in flocculation due to the soft water quality, which lacks essential calcium ions.

Building on this experience and in response to the growing interest in CDR, AVZ has partnered with CREW Carbon and Omya to advance the plant's capacity for carbon removal. CREW Carbon facilitates the monitoring of CO_2 removal and the generation of carbon credits, which are then sold on the voluntary carbon market. This revenue stream helps to finance the ongoing supply of limestone. Omya provides the specialized limestone and collaborates closely to enhance the efficiency of the CDR method.

In June 2024, AVZ began a new phase of experimentation using a finer, more reactive limestone product specifically optimized for CDR. This required investments in a dosing setup and advanced instrumentation. The current dosage is 200 mg of limestone per litre, and this collaborative approach has enabled AVZ to store 1 ton of biogenic CO_2 with every 3.3 tons of limestone used. This initiative not only provides an innovative example of CDR but also highlights the significant co-benefits of the technology for wastewater treatment operations.

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[64] Note: This calculation assumes an average cost of €4,49 per m^3 of freshwater consumed in European households (VAT excluded), covering both freshwater production and distribution (€2,17/m^3) and wastewater collection, transport, and treatment (€2,32/m^3 of which €0,77/m^3 is linked to wastewater treatment and €1,55/m^3 is linked to the wastewater collection and transport). Both assumptions are based on 2025 data from the city of Brussels (Belgium) (Source: Vivaqua (2025) Le tarif linéaire domestique)).

[65] Deloitte (2025) 11 misconceptions about carbon credits and the voluntary carbon market

[66] An average of 140 mg of organic carbon/L of wastewater (Source: Brian H Kiepper (2022) Understanding Laboratory Wastewater Tests) and a conversion factor of 3,67 based on the mole mass of CO_2/mole mass C were used to account for the potential amount of CO_2 emissions from wastewater (Source: Eurofins, How do you calculate how much CO_2 is captured in Organic Matter). The amount of limestone needed to treat 1 kg of CO_2 was assumed to be 3,25kg, and the price of limestone was estimated to be €100/ton. The estimated CO_2 capture rate for wastewater was set to be 20%. These assumptions were based on an expert consultation.

[67] Source: expert visit

Deep dive: biogas upgrading

Wastewater treatment installations are increasingly looking into the valorisation of excess sludge. Anaerobic digestion has gained increasing importance as it enables the production of biogas, which can be combusted to generate renewable energy. More recently, attention has also increased towards biogas upgrading, in which CO_2 is stripped from the methane. This high purity biomethane can then be used as a renewable alternative to natural gas and can even be injected into transmission grids**. The separated CO_2, once viewed merely as a waste stream, now represents a valuable opportunity for climate action, though realizing this potential critically depends on how it is classified and ultimately utilized:**

- For the process to qualify as CDR (often termed Bioenergy with Carbon Capture and Storage, or BECCS, when the CO_2 is from biogenic sources), the captured biogenic CO_2 must be permanently stored in a manner that prevents its re-emission, such as through geological storage or durable mineralisation.

- The biogenic CO_2 can also be captured and used in applications like beverage carbonation (once purified to food-grade standards) or for enhanced crop growth in greenhouses. In these cases, the CO_2 is ultimately re-released into the atmosphere and is therefore rather categorized as CCU (Carbon Capture and Utilisation).

Process design

Before entering the anaerobic digester, sludge from aerobic WWTPs is often pretreated, commonly using methods like thermal hydrolysis, to break down complex organic compounds and enhance its biodegradability. The conditioned sludge is then fed into sealed anaerobic digestion tanks, where microorganisms break down the organic material in the absence of oxygen. This biological process generates a gas mixture (known as biogas), composed primarily of methane (CH_4) and carbon dioxide (CO_2), along with trace amounts of other components.

Following digestion, the biogas can be upgraded to separate the valuable methane from the carbon dioxide and other impurities. One common method involves scrubbing the CO_2 from the biogas. The captured CO_2 can also be further processed, for example, by liquefaction, allowing it to be stored and utilized for various industrial or agricultural applications, such as accelerating plant growth in horticulture. Meanwhile, the remaining digestate is dewatered, with the solid fraction often used as a soil amendment and the liquid portion treated to remove nutrients, such as phosphorus and nitrogen, before being returned to the main wastewater stream.

Economic perspectives

Capital investment

The capital expenditures for a biogas upgrading project are substantial. The key investments include[68]:

- **Biogas upgrading equipment:** This includes the specialized machinery for separating methane from carbon dioxide. Most common methods employed are membrane separation, pressure swing adsorption, water scrubbing and amine scrubbing[69].

- **CO_2 handling equipment:** After stripping the CO_2 from the biogas, it can either be stored on-site and transported via trucks or, if a CO_2 network is available nearby, injected in the grid. Depending on the CO_2 handling method, this requires investments in a CO_2 storage unit, CO_2 truck loading unit or the pipeline equipment.

Operational expenses

The operational expenditures are associated with the day-to-day running of the facility, but these are often offset by cost savings and new revenue streams. Key operational costs include:

- **Energy consumption:** The systems for biogas upgrading and CO_2 handling require energy. **Crucially, the energy used is best sourced from renewable or low-carbon providers to ensure a net climate benefit, as using fossil fuels for this purpose would lower the overall environmental goal.** While this external energy input may come at an additional cost depending on the specific geography, it can be offset by on-site energy production when valorizing the produced biomethane.

- **Maintenance and labour:** Regular maintenance of complex equipment and the labour required to operate the facility are continuous costs.

Cost saving and potential revenue streams

The implementation of a biogas upgrading facility can lead to significant cost reductions and new revenue streams that help to offset the operational costs.

- **Optimized sludge management:** Centralized processing of sludge can optimize operational costs related to sludge transport and disposal.

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[68] IWA Publishing (2020) Water practice & Technology

[69] Anneli Petersson and Arthur Wellinger (2009) Biogas upgrading technologies, developments and innovations

- **Biomethane revenue:** The upgraded biomethane can be injected into the local gas grid and sold, creating a new and significant revenue stream. A portion of this biomethane can also be used on-site to generate heat and electricity, primarily through combined heat and power (CHP) units, reducing the plant's reliance on external energy sources.

- **CO_2 revenue:** The captured CO_2 is a valuable co-product that can be sold to industries like horticulture, providing an additional source of income. The storage of CO_2 can also be valuable for other companies looking to offset their emissions.

Integration with carbon storage after carbon capture

Even though use cases are still limited today, captured CO_2 from biogas upgrading could also be directed toward long-term storage solutions, effectively and permanently locking it away for millennia. **This approach will become even more important as CO_2 capture scales up and the nearby industries that currently consume CO_2 reach their practical limits, leaving more CO_2 than local markets can absorb**.

Different methods for storing captured CO_2 involve the use of dedicated geological formations and innovative mineralisation processes. In Italy, Eni and Snam's Ravenna CCS project will perform CO_2 injection at 3000 meters beneath the Adriatic Sea, aiming to initially capture 25,000 tonnes annually from Eni's Casalborsetti plant (Phase 1), with plans to expand to 4 Mt per year by 2030 (Phase 2). Eventually the project aims to reach a total potential of 16 Mt in the Adriatic Sea's depleted gas fields[70]. Similarly, in Norway, Northern Lights has approved and begun implementing Phase 2 of their CCS system. This expansion increases its CO_2 transport and storage capacity from the initial 1.5 Mt to at least 5 Mt annually. Northern Lights provides open-access, cross-border CO_2 storage and is supported by commercial agreements with multiple European emitters, including CO_2 produced from a bioenergy facility. **Beyond these large-scale geological initiatives, companies like Neustark are pioneering more decentralized forms of permanent CO_2 storage in concrete waste through mineralisation, a method that will be discussed in further detail later in this report.**

Pioneer projects

The Dommel Water Authority, a regional water board in the Netherlands, serves as an excellent example of this approach. At its Tilburg WWTP, the authority embarked on a comprehensive project to build a Water and Resource Recovery Facility (WRRF) to centrally process all sludge generated by its eight WWTPs[71].

The project, which began in 2017, aimed to optimize sludge management, increase biogas generation, and facilitate phosphorus recovery. The facility was then equipped with a Cambi thermal hydrolysis plant, large anaerobic digestion tanks, and advanced sludge dewatering centrifuges, among other technologies. In 2023, the facility added a new dimension to its operations by commissioning a green gas production unit[72]. The facility produces enough biomethane to supply the gas needs of approximately 4,000 homes annually[73]. Furthermore, it produces liquid bio-CO_2, with a volume of around 5.9 million kg annually, which is sold to the horticulture sector to stimulate crop growth[74]. This strategic initiative showcases how a wastewater treatment plant can evolve into a resource recovery hub, creating new value from waste products and contributing to the circular economy. The equipment built at this facility could in the future also be valorized for performing CDR when the captured CO_2 is stored instead of used.

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[70] Ravenna CCS, Our activities in Ravenna

[71] Waterschap De Dommel, Rioolwaterzuivering Tilburg

[72] Waterschap de Dommel (2023) CO_2-prestatieladder Voortgangsrapportage 2023

[73] Bright, CO_2 liquefaction in the Netherlands

[74] AquaMinerals, Green CO_2 Bright future for water authorities and CO_2 purchasers

Deep Dive

Deep dive: biochar production from sludge

Sludge pyrolysis is a thermochemical conversion process that transforms sewage sludge into valuable products in an oxygen-free environment. The end-products still contain the biogenic CO_2 and if stored permanently after the pyrolysis process, they result in CDR.

Process design

Unlike incineration, which combusts waste into CO_2, pyrolysis heats the sludge in an oxygen-free environment to high temperatures, typically ranging from 300°C to 700°C, causing the organic compounds to decompose into mainly solid products, as well as gaseous and liquid products[75]. The fundamental steps of the process involve:

- **Drying and pre-treatment:** Raw sewage sludge, which has high moisture content, is first dewatered and dried. This pre-treatment step is critical for energy efficiency and ensures consistent performance of the pyrolysis reactor[75].
- **Pyrolysis:** The dried sludge is fed into a reactor and heated in the absence of oxygen[76]. As the temperature rises, the sludge breaks down while sequestering CO_2, yielding three main products:
    - **Biochar:** A carbon-rich solid residue that can be used as a soil amendment, resulting in CDR, or solid fuel[77].
    - **Bio-oil:** A liquid mixture of organic compounds that can be refined into fuels or chemicals.
    - **Syngas:** A combustible gas, primarily composed of hydrogen, carbon monoxide, and methane, which can be used for energy generation within the plant itself[75].
- **Product separation:** The hot vaporized products are cooled and condensed to separate the bio-oil from the non-condensable syngas. The syngas is then cleaned of impurities, and the biochar is collected from the reactor[78].

The ratio of these products can be adjusted by varying the pyrolysis temperature and the duration of the process, with higher temperatures generally favouring syngas production over biochar.

If the biochar, syngas or bio-oil are stored underground, or biochar used as soil amendment, it directly results in CDR. If they are used as fuel or as feedstock (e.g. in industrial processes, such as steel making), they are used for CCU rather than CDR. However, if the released CO_2 is still sequestered after use (e.g. CO_2 capture and storage after biochar incineration), it can still contribute to CDR.

Economic perspectives

Capital investment

For a company looking to implement sludge pyrolysis technology, the capital expenditure primarily includes the cost of the main technological installations and associated civil works. A typical pyrolysis facility requires the following key installations:

- **Dewatering and drying system:** Equipment to reduce the moisture content of the incoming sludge to prepare it for pyrolysis. This can include belt presses, centrifuges, and thermal dryers.
- **Feeding system:** A robust system to feed the dried sludge consistently and safely into the reactor, preventing oxygen from entering the sealed environment.
- **Pyrolysis reactor:** This is the core component of the plant. A well-designed reactor is essential for efficient and consistent heat transfer to the sludge.
- **Condensation unit:** A system to cool the pyrolysis gases and condense them into bio-oil and process water.
- **Syngas cleaning system:** Scrubbers and filters to remove impurities from the syngas, ensuring it is suitable for use as a fuel.
- **Storage and handling facilities:** Tanks for storing the bio-oil, silos for the biochar, and a system for managing the syngas.

Operational expenses

- **Energy consumption:** The plant requires energy for the drying process and to heat the pyrolysis reactor. However, this cost can be largely offset by the energy recovered from the process. The syngas produced is a reliable fuel source and can be used to power the drying and pyrolysis stages, making the system highly self-sufficient.
- **Maintenance and labour:** Regular maintenance of complex equipment and the labor required to operate the facility are continuous costs.

Savings and potential revenue streams

- **Sludge disposal costs:** A major saving is realized by eliminating or drastically reducing the cost of managing sludge, including the transport, landfilling or incineration of sludge. Pyrolysis can reduce the volume of sludge by more than 85% and mass by up to 90%, leading to significant savings in transportation and disposal fees.
- **Revenue generation:** The bio-oil, syngas, and biochar are valuable products. Bio-oil can be sold as a fuel or raw material for industrial processes. The syngas can be used on-site for heat and electricity, reducing energy bills. Biochar can be sold as a soil amendment, contributing to carbon sequestration and creating a new revenue stream.
- **Carbon credits:** The removal of biogenic GHGs can qualify for the generation of carbon credits that can be traded on voluntary markets, and potentially future compliance markets. Selling these credits represents a significant potential revenue stream that directly monetizes the environmental benefit of the process, thus further offsetting operational costs and improving the overall economic viability of the technology.

Pioneer projects

Several pioneer projects are demonstrating the viability of sludge pyrolysis technology. The Danish engineering company AquaGreen has developed a unique, integrated steam-drying and pyrolysis solution, branded as HECLA technology. This patented process is designed to transform wet biomass, such as sewage sludge, into valuable products without the need for auxiliary fuel. One of its key installations is at a municipal wastewater treatment plant in Fårevejle, Denmark.

AquaGreen's technology not only reduces sludge volume and transportation needs by up to 90%, but also effectively removes hazardous substances like PFAS, and recirculates critical nutrients like phosphorus. The biochar produced by the process is sold as a nutrient-rich fertilizer and soil improver, creating a new revenue stream for the company. The process is energy-positive, using the energy embedded in the sludge itself to power the system, with excess energy available for district heating.

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[75] Cambi, Slude pyrolysis: Exploring Benefits and Limitations

[76] Lei, S. et al. (2016). Co-production of biochar, bio-oil, and syngas from Tamarix chinensis biomass under three different pyrolysis temperatures.

[77] Pradhan, S. et al. (2024). Biochar – Recovery Material from Pyrolysis of Sewage Sludge: A Review.

[78] Beston Group, Pyrolysis Process: A Step-by-Step Guide.

Conclusions and limitations

A significant set of challenges emerges when considering the integration of novel technologies for CDR in WWTPs.

Primarily, WWTPs often operate in a strict regulatory environment, typically managed by public or quasi-public entities. This operational structure inherently fosters a risk-averse approach to technological experimentation and adoption. In addition, WWTPs do not fall under the EU ETS (Emissions Trading Scheme) regulation, leading to fewer incentives to reduce their GHG emissions.

Furthermore, a critical challenge pertains to carbon accounting. WWTPs frequently operate with limited or no direct GHG emission reporting obligations, and their biogenic emissions are often considered "zero-rated" within broader municipal inventories. Consequently, a substantial hurdle lies in developing robust methodologies and clear guidelines for accurately incorporating negative carbon fluxes resulting from interventions like wastewater liming into overarching municipal net emission accounting. This raises the fundamental question of whether such negative emissions can be appropriately quantified and offset against other emission sources within a municipality's comprehensive carbon inventory.

The proposed policy recommendations to address these challenges are covered in the chapter on conclusions and policy recommendations.

Carbon dioxide removal opportunities in the concrete recycling sector

Sector overview in Europe

Annually, ~290 Mt of concrete waste is generated from the demolition of buildings and other infrastructure in the EU[79], representing 1/3rd of all Construction and Demolition Waste (C&DW). Most of the generated concrete waste (~80%)[80] is collected from demolition sites and transported to recycling facilities where it is sorted, treated, and crushed into recycled concrete aggregates (RCA). These granulates are mainly used as a base material for road construction. In some cases, however, high-quality concrete waste is sold to concrete manufacturers, where the RCA is mixed with primary raw materials to produce new concrete. The concrete waste that is not recycled is used for backfilling (~11%)[81] or disposed of in landfills (~9%)[82].

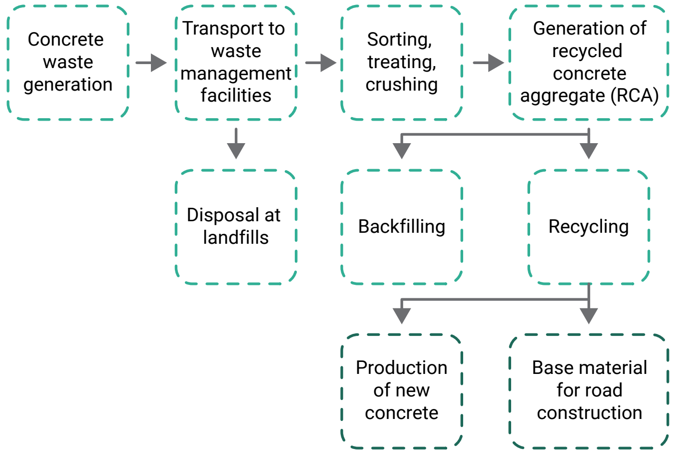

Figure 5: Flow of C&DW in Europe [83]

The balance of greenhouse gas (GHG) emissions during the life cycle of concrete

Production of concrete

The majority of emissions related to concrete production stem from the creation of cement, its key binding ingredient. These represent approximately 68% of total emissions related to concrete production[84]. **At the global level, cement manufacturing accounts for roughly 8% of total CO_2 emissions[85] which are mostly found in the following two processes:**

- **Calcination of limestone:** This thermochemical reaction is the largest single source of emissions. When limestone ($CaCO_3$) is heated to about 1450°C in a kiln, it decomposes into lime (CaO) and releases a substantial amount of CO_2. This process, known as calcination, accounts for approximately 60% of the total emissions from cement production[86]. For reducing emissions, the industry is evolving to using low clinker cement, lowering the need for calcination, as well as introducing infrastructure for carbon capture and storage (CCS)[87].

- **Fossil fuel combustion:** For cement manufacturing, immense heat is needed for calcination and the formation of clinker. While this process has traditionally relied on burning fossil fuels like coal, petcoke, or natural gas, the industry has significantly increased its use of alternative fuels. In 2021, these alternative fuels accounted for 53% of the sector's fuel mix in the EU, a substantial increase from 46% in 2017[87]. The combustion of these fuels, both fossil and alternative, releases CO_2, contributing to approximately 40% of the total emissions from cement production[88].

For the concrete production itself, the energy consumption of heavy machinery used for mixing, pouring, and finishing the concrete also adds to the total carbon footprint, linked to 13% of total emissions.[89]

Other greenhouse gas (GHG) emission fluxes in the concrete lifecycle

While cement production is the main driver of GHG emissions production, other stages of the concrete lifecycle also contribute and some result even in the uptake of GHG emissions. These can be broken down into four main categories:

- **Raw materials:** Emissions are generated during the extraction, mining, and processing of other raw materials used in concrete, such as aggregates (sand and gravel) and supplementary cementitious materials (SCMs) like fly ash or slag[89].

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[79] Note: The total amount of waste in the construction sector is 862 Mt. According to Interreg Europe and Cembureau, at least one third of the total construction and demolition waste is concrete. This mostly aligns with the amount of mineral waste from construction and demolition which is 302 Mt. Source: Eurostat (2025) Generation of waste by waste category, hazardousness and NACE. & Interreg Europe (2022) Collection and recycling of construction and demolition waste & Cembureau, Circularity & Construction.

[80] Note: Estimation based on data by Eurostat (Treatment of waste-by-waste category, hazardousness and waste management operations [env_wastrt]). Percentages based on treatment methods of mineral waste.

[81] Note: Backfilling refers to any recovery operation where suitable non-hazardous waste is used for purposes of reclamation in excavated areas or for engineering purposes in landscaping. Waste used for backfilling must substitute non-waste materials, be suitable for the aforementioned purposes, and be limited to the amount strictly necessary to achieve those purposes.

[82] Note: Estimation based on data by Eurostat (Treatment of waste-by-waste category, hazardousness and waste management operations [env_wastrt]). Percentages based on treatment methods of mineral waste.

[83] Note: Image based on input from: Caro, D. et al. (2024) Environmental and socio-economic effects of construction and demolition waste recycling in the European Union.

[84] Note: Estimation based on data by Walach D. et al. (2016) Effect of Concrete Mix Composition on Greenhouse Gas Emissions over the Full Life Cycle of a Structure and Nielsen C. V. (2008) Carbon footprint of concrete buildings seen in the life cycle perspective

[85] Andrew, R. M. et al. (2018). Global CO_2 emissions from cement production.

[86] World Resources Institute (2022) Laying the Foundation of Cement and Concrete Decarbonization

[87] Cembureau (2024) Cembureau Net Zero Roadmap

[88] World Resources Institute (2022) Laying the Foundation of Cement and Concrete Decarbonization

[89] Gursel A. P. et al. (2014) Life-cycle inventory analysis of concrete production: A critical review

GHG emissions per m_3 of concrete (Total GHG emissions: ~440 kg CO_2eq / m^3)

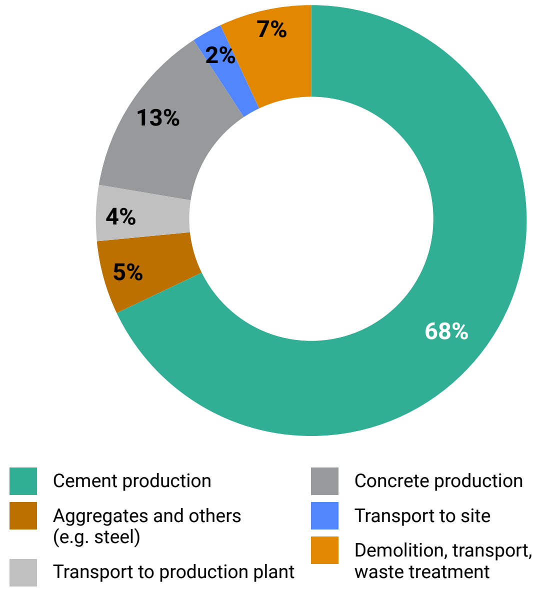

Figure 6: Visual representation of total GHG emissions generated in concrete production. [94]

- **Transportation:** Emissions occur during the transportation of the raw materials, or the finished concrete to construction sites, accounting for approximately 6% of total emissions linked to concrete production[90].
- **Carbonation during the lifespan of the built structure:** During the curing of the concrete, the natural process of carbonation allows the concrete to reabsorb CO_2 from the atmosphere. This occurs when calcium compounds react with atmospheric CO_2 and moisture to form stable calcium carbonates, essentially mineralizing the gas. This process slowly continues throughout the built structure's life. It, however, is constrained due to a limited exposure between CO_2 and the inner concrete structure due to the low surface area that is in contact with the air[91].
- **End-of-life:** At the end of a concrete structure's service life, emissions are generated during demolition and waste management. This includes the energy used for transporting concrete waste to recycling facilities and the energy consumed during the crushing and processing of the waste for reuse. These represent ~7% of total emissions linked to concrete production[92]. This crushing process, however, accelerates the natural process of carbonation, allowing the concrete to reabsorb additional CO_2 from the atmosphere[93,94]

Carbon accounting of these emission streams

Carbon accounting for concrete production and waste management follows established methodologies from frameworks like the GHG Protocol (for corporate reporting) and the United Nations Framework Convention on Climate Change (UNFCCC) (for national reporting). These systems categorize emissions to provide a clear and comprehensive GHG footprint.

The UNFCCC (which follows the Intergovernmental panel on climate change (IPCC) guidelines) includes specific guidelines on the emissions of cement[94] production and energy related emissions[95]. Within these frameworks fossil and biogenic CO_2 recovery and capture could be accounted for. Although the IPCC recognizes that concrete carbonation occurs during the material's life, it currently does not account for this negative emission due to its very slow rate (years to centuries)[96]. End-of-life carbonation from crushed concrete waste is also currently excluded from standard GHG accounting. However, the IPCC is expected to provide a framework for its inclusion in its upcoming methodology report on CO_2 removal technologies, due in 2027[97,98].

Within the GHG Protocol, process emissions from the calcination of limestone and the combustion of fossil fuels used to power the cement kilns or the different mining and processing equipment, are accounted for under scope 1 emissions. Scope 2 emissions account for the indirect emissions from purchased electricity used in the manufacturing process. Scope 3 emissions, cover the emissions from the entire supply chain. This includes all transportation, and the emissions embedded in the production of other materials like aggregates and admixtures[99].

It must be noted however that the GHG protocol is currently developing its "Land Sector and Removals Guidance" which provides companies with detailed rules for measuring and reporting GHG emissions and removals in GHG inventories specifically associated with, among other techniques, carbon dioxide removal technologies[101]. In the current draft, accounting requirements state that reporting removals is optional, and that companies need to separately account for removals based on their sink process (i.e. technological or biogenic sinks) and storage pool (i.e. land based storage, product storage, or geologic storage). Furthermore, the draft outlines specific requirements for GHG removals accounting such as: ongoing storage monitoring or traceability.

Building on these frameworks, the Science Based Targets initiative (SBTi)[102] allows companies to voluntarily validate near-term (5–10 year) and long-term targets, requiring often a reduction of 90 - 95% of scope 1, 2 and 3 GHG emissions by 2050. Within this framework, the SBTi provides specialized sectoral guidance for cement[103], which includes distinct target-setting methods for clinker-producing versus non-clinker-producing companies. This guidance specifies that while natural cement recarbonation currently cannot count toward emission reduction targets, it is being explored as a mechanism to neutralize residual emissions once a company has achieved its long-term deep decarbonisation goals.

The opportunity for CDR in concrete recycling

The concrete sector, while a significant source of GHG emissions, offers a unique and promising avenue for CDR at its end-of-life stage. **This opportunity lies in transforming concrete waste from a byproduct into a valuable resource that sequesters atmospheric or biogenic CO_2.** This section zooms in on realizing CDR through concrete mineralization.

CDR through carbon mineralization of concrete waste

The primary and most utilized method for achieving CO_2 sequestration within concrete waste is through carbon mineralization, a process that permanently stores CO_2 by chemically binding it within the concrete material. This process, which has been observed in nature's long-term carbon cycle, involves two main phases[104]:

- The primary alkaline component in concrete reacting is calcium hydroxide or Portlandite. It reacts with CO_2 according to the formula below, sequestering the CO_2:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

- While the fastest carbonation step involves calcium hydroxide, the majority of the carbon removal capacity in crushed concrete comes from the uptake of CO_2 by calcium silicate hydrate gel (C-S-H, with C = CaO, S = SiO_2 and H = H_2O), according to the formula below:

$$\underset{\text{(Calcium Silicate Hydrate Gel)}}{\text{C-S-H}} + CO_2 \rightarrow CaCO_3 + \underset{\text{(Silica Gel)}}{(SiO_2 \text{ x } nH_2O)}$$

A key application of these reactions is enhanced carbon mineralization of RCAs, where the reaction between CO_2 and demolished concrete is intensified. The resulting CO_2-enriched RCA can then be reused in new applications, such as road construction or as a raw material for new concrete production. **This process not only provides a permanent storage solution for CO_2 but also enhances the value and performance of the recycled material.** It can for example reduce porosity and water absorption of the RCAs, increase their density and strength, and enhance durability.

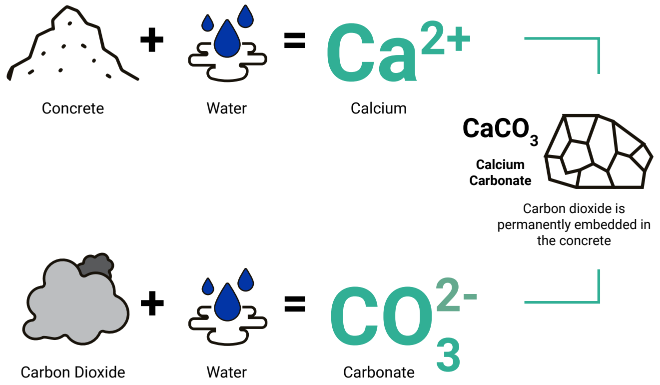

Figure 7: Visualisation of the CO_2 mineralisation process[100]

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[90] Note: Estimation based on data by Walach D. et al. (2016) Effect of Concrete Mix Composition on Greenhouse Gas Emissions over the Full Life Cycle of a Structure and Nielsen C. V. (2008) Carbon footprint of concrete buildings seen in the life cycle perspective

[91] Xi F. et al (2016) Substantial global carbon uptake by cement carbonation

[92] Note: Estimation based on data by Walach D. et al. (2016) Effect of Concrete Mix Composition on Greenhouse Gas Emissions over the Full Life Cycle of a Structure and Nielsen C. V. (2008) Carbon footprint of concrete buildings seen in the life cycle perspective

[93] MPA the concrete center, Concrete carbonation

[94] Note: Estimation based on data by Walach D. et al. (2016) Effect of Concrete Mix Composition on Greenhouse Gas Emissions over the Full Life Cycle of a Structure and Nielsen C. V. (2008) Carbon footprint of concrete buildings seen in the life cycle perspective

[95] IPCC (2006) 2006 IPCC Guidelines for GHG Inventories - Energy

[96] IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories – Mineral Industry Emissions – Cement Production

[97] IPCC (2023) Climate Change 2023: Synthesis Report

[98] MPA The Concrete Sector, Concrete carbonation & IPCC (2024) Call for nomination of experts to Scoping Meeting for Methodology Report on Carbon Dioxide Removal Technologies and Carbon Capture Utilization and Storage & IPCC (2024) Expert meeting on CDR Technologies

[99] GHG Protocol (2015) corporate standard & guidance on Scope 2 and 3 emissions

[100] The Singapore Engineer (2021) A game changing technology

[101] GHG Protocol (2016) Land Sector and Removals Guidance

[102] Science based targets

[103] SBTi (2022) Cement Science Based Target Setting and Guidance

[104] Zhang et al. (2017) Review on carbonation curing of cement-based materials

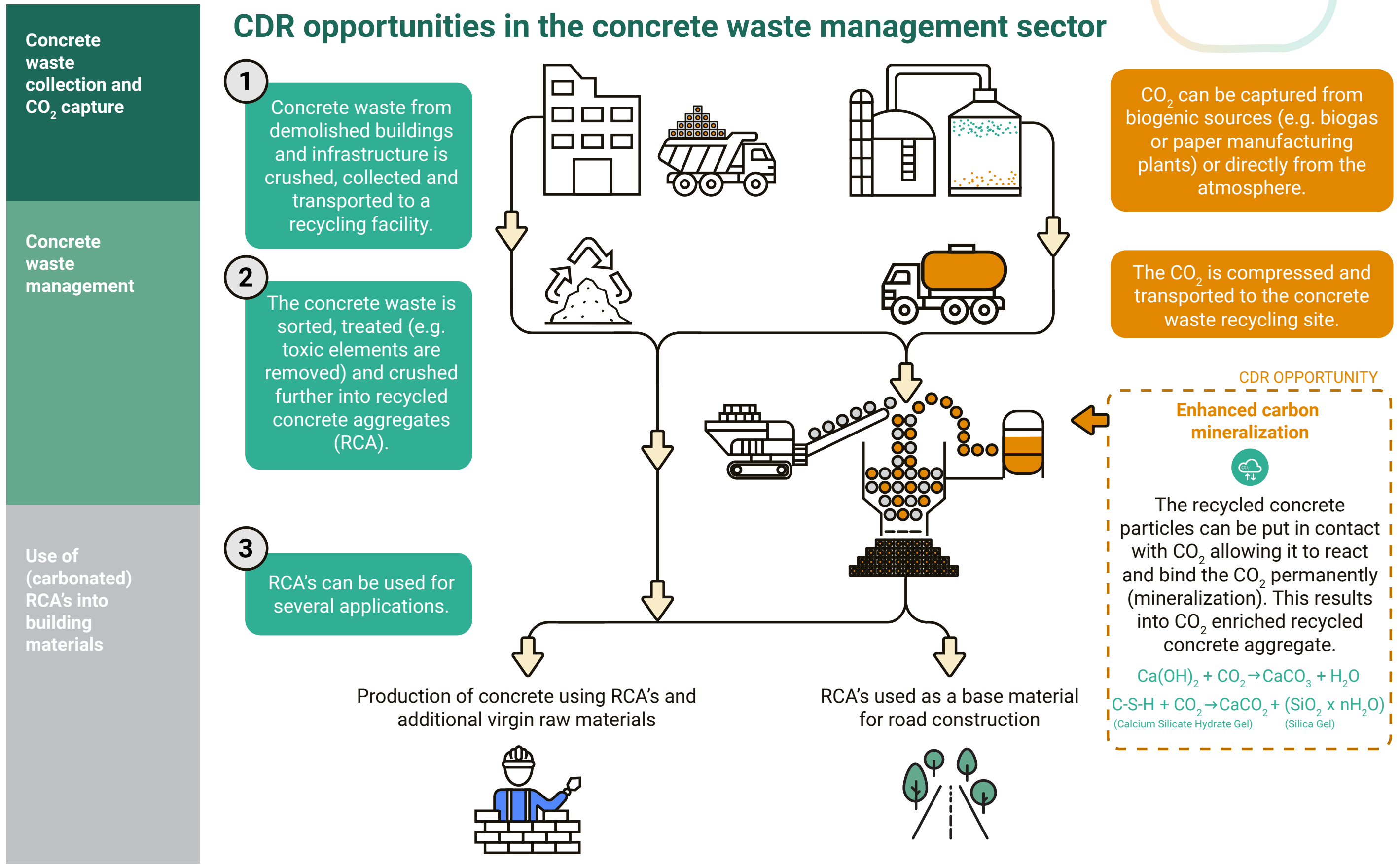

Figure 8: CDR opportunity in the concrete waste management sector.

Insight: In addition to enhanced carbon mineralisation, recent research has also investigated the use of finely crushed concrete waste for enhanced rock weathering (ERW) as soil additive for increasing the soil pH but also sequestering CO_2 from the atmosphere. When the fine concrete powder is spread across agricultural land, the main reactive component calcium hydroxide ($Ca(OH)_2$) is exposed. This highly alkaline material reacts rapidly with CO_2 and rainwater, ultimately transforming it into stable, dissolved **bicarbonates** (HCO_3^-) that end up into rivers and eventually are transported to the ocean for **permanent sequestration**. Crucially, this process delivers a dual benefit: it achieves significant carbon removal while simultaneously acting as a **soil amendment** to improve the quality of the land and boost crop yields. Even although this is another CDR opportunity for concrete waste that should be further invested into, **it is out of the scope of this study** which focuses on the recycling of concrete waste into new building materials.

Potential scale of CDR in concrete waste management

With 230 Mt of concrete waste being annually recycled already today in the EU[105], it is estimated that between 2.3 Mt and 5.7 Mt of CO_2 could be theoretically sequestered in RCA each year[106]. This number could potentially increase to between 2.6 Mt and 7.2 Mt of CO_2 per year if 100% of the concrete waste generated in the EU is recycled. This GHG reduction potential is above the current GHG emissions that are associated with the processing of concrete waste into RCA[107].

At the global level, with 50%[108] of the 1.5 Gt of concrete waste produced annually[109] being recycled, it is estimated that between 7.6 Mt and 18.9 Mt of CO_2 per year could be theoretically sequestered in RCA. This number could potentially increase to between 15.1 Mt and 37.8 Mt of CO_2 per year if 100% of the concrete waste generated in the world is recycled.

The more practical total potential of CO_2 mineralization in concrete waste will be lower and will depend on the affordability of integrating this technology in the existing operations of concrete waste recyclers, favouring recycling sites that operate at a larger scale.

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[105] Note: This amount was based on the following assumptions:
- The total amount of waste in the construction sector is 862 Mt (Data from Eurostat – wasgen database – NACE code F(Construction).
- According to Interreg and Cembureau at least one third of the total construction and demolition waste is concrete.
- 80% recycling estimation is based on data by Eurostat (Treatment of waste by waste category, hazardousness and waste management operations [env_wastrt]). Percentages based on treatment methods of mineral waste.

[106] Note: According to existing market players, a range of 10kg-25kg of CO_2 can technically be injected and stored per ton of RCA. See: neustark | FAQs

[107] Note: Based on the assumption of 10 kg of CO_2(eq) GHG emissions to produce one ton of RCA from construction and demolition waste. To process 230 Mt of concrete waste, this results in 2.3 Mt of GHG emissions. This value is derived from literature (Source: Hosseini, S.A. et al. (2025) Cross-country life cycle assessment of construction and demolition waste recycling with evaluation of energy use, carbon emissions, and regional trade-offs. & Concrete Europe (2016) Closing the loop, what type of concrete re-use is the most sustainable option?)

[108] Note: 50% recycling rate is an own assumption.

[109] Note: Own calculation based on data from the World Bank (What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050), assuming 1/3rd of global construction and demolition waste is concrete waste and a recycling rate of 50%.

Deep dive: enhanced carbon mineralization of concrete waste

Carbon mineralization is a natural process where concrete waste reacts with CO_2 from the atmosphere. By accelerating and optimizing this reaction, we can effectively and permanently bind captured CO_2 to concrete waste, thereby turning a waste product into a long-term carbon sink.

Process design

The enhanced carbon mineralization process begins with the pre-treatment of concrete waste. This stage involves the crushing and sieving of demolition waste into aggregates to achieve a specific particle size distribution, which is essential for its re-use further on in the value chain. Crushing also increases the surface area of the concrete waste, which has a positive effect on the carbonation reaction.

The next step is the carbonation of the concrete waste, which can be done using one of two main methods: gas-solid carbonation, which involves exposing the solid concrete to CO_2 gas; or liquid-solid carbonation, which uses a liquid to help transfer the CO_2 to the solid particles, often resulting in a faster reaction. **Each method has its own benefits depending on the application.**

01. Gas-solid carbonation

This method, which is the most widely applied in the industry, involves placing recycled concrete RCAs in a closed reactor or chamber. The chamber can be designed as a fixed-bed, rotating[110], or a fluidized-bed[111] system. A gas stream with a high concentration of carbon dioxide is then introduced into the reactor. To optimize the reaction between the carbon dioxide and the RCA particles, the temperature and relative humidity are often maintained at specific levels. The moisture is crucial as it allows the CO_2 to dissolve and form carbonic acid (H_2CO_3), which then reacts with calcium hydroxide ($Ca(OH)_2$) and calcium silicate hydrate (C-S-H) gel phases to form $CaCO_3$[112]. In some cases, the RCA is moistened before the reaction takes place, which can lead to a higher efficiency[113].

02. Wet Carbonation (Liquid-Solid Carbonation)

In the wet carbonation process, a liquid medium, typically water, facilitates the reaction. This approach is particularly well-suited for fine recycled concrete aggregates, as the liquid enhances the mass transfer of carbon dioxide and increases the total surface area for reaction. While this method generally achieves a higher carbonation efficiency compared to dry processes, its implementation is more complex, making large-scale deployment challenging.

To improve carbonation efficiency and the quality of recycled concrete aggregates, several pre-treatment and process methods can be used: conducting the reaction at elevated pressures, for example, speeds up the process by increasing the solubility of carbon dioxide.

Economic perspectives

Capital investment

The capital expenditures for a carbonation plant are primarily driven by the cost of specialized equipment and the scale of the operation. The total investment can range significantly, but key components include:

- **Crushing, sieving and moving equipment:** Acquiring robust crushers, sieving and moving machinery to process demolition waste into the required aggregate size and feeding the reactor is a major factor in the overall capital cost. This equipment, however, might already be present at the concrete waste recycling facility.
- **Reactor/chamber system:** This is the core of the process. For gas-solid carbonation, this involves purchasing and installing specialized reactors, such as fixed-bed, rotating, or fluidized-bed systems. For wet carbonation, large tanks and mixing equipment are required.
- **Gas handling and storage:** A system for sourcing, storing, and delivering high-concentration CO_2 is essential. This includes compressors, gas storage tanks, as well as evaporators to convert liquid CO_2 again into a gas to be used in the reactor.
- **Instrumentation and control systems:** To ensure process optimization and safety, investments in sensors, monitoring equipment, and automated control systems are necessary. These systems regulate temperature, pressure, humidity, and CO_2 flow rates to maintain ideal reaction conditions.

Operational expenses

The operational costs associated with enhanced carbon mineralization are influenced by energy consumption, raw material costs, and labour. The main operational costs include:

- **Energy consumption:** The primary energy users are the crushing equipment, the CO_2 compressors, and the heating and cooling systems that regulate the temperature inside the reactors. The energy required to move materials and run control systems also contributes to this expense.
- **Cost of CO_2:** While the goal is to store CO_2, there is still a cost associated with its capture and transport to the facility. The cost of CO_2 itself is a critical operational expense, and prices can fluctuate significantly by region.

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[110] Dos Reis et al. (2021). Coupling of attrition and accelerated carbonation for CO_2 sequestration in recycled concrete aggregates.

[111] Note: Fluidized-bed reactor: A type of chemical reactor where a fluid (gas or liquid) is passed upwards through solid particles, causing them to behave like a fluid.

[112] Zhong, W. et al. (2025). Effects of Different Carbonation Treatment Methods for Recycled Concrete Aggregate.

[113] Bergmans, J et al., (2024). Carbonation of recycled concrete aggregates for new concrete and concrete fines to make cement-free hollow blocks. Sustainability.

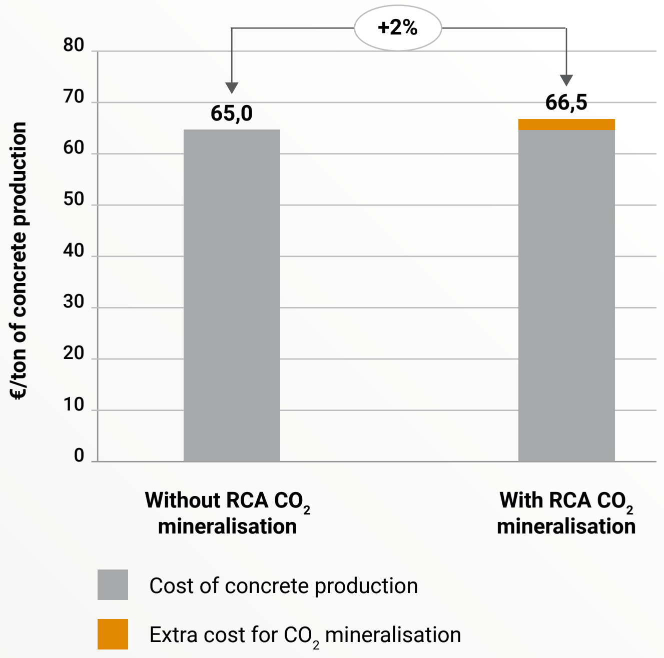

Figure 9: Marginal cost increase of integrating CO$_2$ removal in concrete production. Both variants include RCA, one includes CO$_2$ mineralized RCA.

- **Maintenance and labour:** The regular maintenance of heavy machinery, such as crushers and reactors, is a continuous cost. Additionally, skilled labour is required to operate the sophisticated equipment, monitor the process, and manage the logistics of waste intake and aggregate output.

- **Water usage:** In wet carbonation and other processes that require moisture, the cost of water and its potential treatment for re-use must be considered. While not as significant as energy or CO$_2$ costs, it is a factor in total operational expenses.

Impact on the current cost of concrete production

Practitioners working in the concrete waste carbonation field suggest that concrete carbonation is at technology readiness level (TRL) 8[114], as it is already successfully deployed at multiple sites. Based on exchanges with the sector, it is estimated that the cost of producing concrete, including carbonated RCAs instead of conventional RCAs, would increase by approx. 1-2%[115], depending on the additional uptake of 10-25 kg CO$_2$ for each tonne of RCA. This cost could further go down as the technology becomes more mature and doesn't consider any additional revenues (e.g. carbon credits).

Since the cost of the concrete material itself is only a smaller part of the total building cost of a project (e.g. single-family home, commercial building, bridge, etc.), the additional cost of performing RCA carbonation would be almost negligible compared to the total project cost (<<1%).

Potential costs savings

The application of the carbon mineralization technology to concrete waste could also result in notable savings, which can partially or fully offset the costs mentioned above. These aspects were not yet considered in the cost analysis above. These savings include:

- **Improved material properties:** The carbon mineralization process enhances the physical properties of the recycled aggregates, such as increasing their strength and reducing water absorption. This improved quality allows them to be used in higher-grade concrete applications, e.g. high-rise buildings and infrastructure compared to non-structural elements, which can command a higher market price compared to standard recycled aggregates.

- **Carbon credits:** The application of carbon mineralization on concrete waste results in measurable and permanent CO$_2$ sequestration which can qualify for the generation of tradable carbon credits in voluntary markets. Selling these credits represents a significant potential revenue stream that directly monetizes the environmental benefit of the technology, thus further offsetting operational costs and improving the overall economic viability of processing construction and demolition waste.

Pioneer projects in carbon mineralisation of concrete waste

Since their foundation in 2019, Neustark has been collaborating with concrete waste recyclers to operate CO$_2$ storage installations that inject CO$_2$ into the concrete waste recycling process to achieve effective CDR. The CO$_2$ is from biogenic origin that is captured in biogas upgrading plants before being liquefied and transported to the concrete waste recycling site. On site, the CO$_2$ is de-liquefied and injected into the concrete waste recycling process without causing any disturbance to the recycling operations. By the end of 2025, the company is operating 44 carbon capture and storage sites in Switzerland, France, Germany, Austria, Belgium, Italy and England, and has permanently removed almost 6 kt of CO$_2$[116]. The key characteristics of Neustark's CDR solutions are as follows:

- **Customizable**: Neustark's technology is compatible with most concrete waste recycling sites, especially those with a high material throughput (> 80 kt of concrete waste annually). Much of the equipment is off-the-shelf, ensuring ease of implementation. The injection of CO$_2$ can be calibrated to deliver precise amounts based on target CO$_2$ capture levels. Additionally, the system requires minimal maintenance.

- **Quantifiable CO$_2$ removal process**: The enhanced CO$_2$ mineralisation technology operates within a closed system and utilises sensors for inlet and outlet monitoring, ensuring that the CO$_2$ removal process is quantifiable.

Depending on the CO$_2$ transportation distances, the selling price of removing one tonne of CO$_2$ ranges from €350 to €500, which is in line with the average cost related to Bioenergy with Carbon Capture and Storage (BECCS)[117]. Currently, Neustark sells carbon credits on the voluntary carbon market, and uses the associated revenues to finance the CO$_2$ capture and associated logistics costs. So far, Neustark has developed several flagship projects that have the capacity to remove over 1,000 tonnes of CO$_2$ annually. Some examples include:

- **Möckli Beton AG**: Neustark's storage technology has been integrated into the production process of Swiss concrete recycler and producer Möckli Beton AG[118].

- **Heim**: Neustark's first project in the EU is a collaboration with Berlin-based construction and recycling company Heim. This project involves storing CO$_2$, which is sourced from MVV's biowaste fermentation plant in Dresden[119].

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[114] Note: A technology at TRL 8 (Technology Readiness Level 8) reflects the technology is qualified through testing and demonstration in its final configuration and expected operational environment.

[115] Note: Analysis based on: assumed price of concrete of 65 EUR/tonne (Calculation based on data in Checkatrade); 57% of the concrete being coarse aggregates of which 30% are replaced by RCA; the potential of RCA to absorb 10-25 kg CO$_2$ per tonne of RCA (Neustark); the cost of capture storage and transport of CO$_2$ being approx. 350 EUR/tonne (Engagement with industry experts). Source: Checkatrade (2024) What is the cost of ready mix concrete per m3?

[116] Neustark. Get to know neustark

[117] Deloitte (2025) 11 misconceptions about carbon credits and the voluntary carbon market

[118] Neustark (2025) Storage partner Mockli breaks CO$_2$ removal record

[119] Neustark (2023) Neustark launches the first commercial site for permanent CO$_2$ storage in the EU

[120] Neustark (2023) We remove CO$_2$ from the atmosphere – and store it permanently

Conclusions and limitations

While the potential for CDR in concrete waste management is clear, successfully scaling these techniques beyond pilot projects presents several technical and economic hurdles. The theoretical capacity to sequester Mt of CO_2 is a powerful motivator, but moving from a proven concept to a widespread, commercially viable solution requires addressing a range of challenges. The primary limitation isn't a lack of technological feasibility; it's the complexity of integrating these solutions into existing industrial supply chains. Issues range from the additional energy costs associated with carbon capture and utilization to the logistical difficulties of transporting CO_2 and concrete waste to specific sites. Furthermore, the economic viability of these CDR products can be uncertain, as they must compete with traditional, often cheaper, building materials.

The following section explores these challenges in detail, examining why the widespread adoption of CO_2 mineralization and other concrete-based CDR methods faces a steep path to market:

- **The availability of high-quality concrete waste** suitable for CO_2 injection is essential for the effective uptake of CO_2. Not all concrete waste is correctly sorted initially, limiting its use. Regarding the supply of concrete waste, there are limitations based on location. While urban areas offer an abundant supply conducive to a CO_2-efficient chain, remote regions face inconsistent availability, where transportation emissions could negate the CO_2 injection benefits. Without both a consistent and qualitative stream of concrete waste, the mineralisation process cannot achieve its full potential.

- Additionally, the **proximity of CO_2 sources** to concrete recycling sites is crucial for cost-effective CDR. The proximity of CO_2 capture plants has a direct effect on the total energy used during the process, and the efficiency of the CO_2 sequestration.

- **Administrative burdens** also pose a significant challenge. The categorisation of CO_2 as waste, along with bureaucratic requirements for transboundary CO_2 transport, adds layers of complexity and contributes to higher overall costs. Moreover, obtaining building permits for the necessary installations can be a lengthy process, hindering the scaling of the CO_2 mineralisation technology, especially as the permitting processes may be different from one country to another, or even on a local scale.

- **Lack of willingness from concrete buyers to pay for the premium price** of CO_2-enriched concrete is a critical limitation. Without sufficient market demand, the incentive to produce CO_2-enriched concrete diminishes, affecting the commercial viability of the process. In this context, low-carbon labelling of the CO_2-enriched concrete that reflects the reduced CO_2 intensity achieved through CDR can become increasingly important, especially as the EU and other regions are starting to implement carbon border adjustment mechanisms (CBAM). CBAM will consider the CO_2 embedded emissions of materials for tax provisions at a cross-border level. As soon as concrete or aggregates would become part of a CBAM, inclusion of performed CDR activities in their CO_2 labelling could help companies demonstrate the lower carbon footprint of their products, facilitating market access and potentially reducing CBAM-related costs or tariffs.

The proposed policy recommendations to address these challenges are covered in the chapter on conclusions and policy recommendations.

Carbon dioxide removal opportunities in the mining waste management sector

Overview of the mining sector and mining waste management in Europe

A renewed interest in the mining sector in the EU

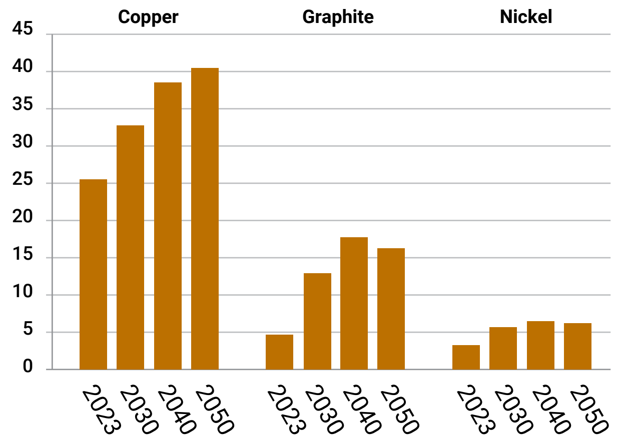
The production of essential components and equipment that are of strategic importance for the EU, such as batteries, renewable energy technologies, digital devices, and defence equipment, require critical raw materials[121] (CRMs) (e.g., lithium, manganese, cobalt, nickel, platinum, rare earth elements, etc). Despite their critical role, over half of the 34 CRMs identified by the EU are currently being imported from third countries at rates exceeding 80% by volume[122]. The supply of many CRMs is currently highly concentrated in a small number of countries. As a result, European supply chains have become highly vulnerable to political instability, geopolitical risks, and potential export restrictions[123] which significantly threatens the EU's resilience and technological autonomy. **In a context where the demand for many of these essential components and equipment is expected to significantly increase in the next years and decades, such structural vulnerabilities in EU CRMs supply chains pose significant risks to the EU's resilience and technological autonomy[124].**

To face such dependence and vulnerability, the EU adopted in 2024 the Critical Raw Materials Act[126] (CRMA). While the primary goal of the CRMA is to strengthen the European raw material value chain and diversify supply, it explicitly puts recycling and sustainability as a central element of this strategy. The Act identifies key strategic raw materials that are most crucial for technologies with a focus on energy, digital, defence and aerospace applications (e.g., copper, nickel, manganese, lithium phosphorus, etc.). The CRMA sets benchmarks along the strategic raw materials value chain on EU extraction, processing, and recycling of strategic raw materials (10%, 40% and 25% of EU's annual demand by 2030, respectively)[127].

To execute this, in March 2025, the European Commission selected 47 European projects focusing on extraction, processing, recycling, and substitution to be awarded the status of 'strategic projects' under the CRMA[128]. These projects will benefit from coordinated support from the Commission, the Member States, and financial institutions, particularly in terms of access to finance, the granting of permits and help in linking up with the off takers. This first list of strategic projects aims to ensure that the EU can fully meet its extraction, processing, and recycling 2030 benchmarks for lithium and cobalt, while making substantial progress for graphite, nickel, and manganese.

Mining waste management

Global demand forecasts in Mt of key minerals to reach net zero by 2050



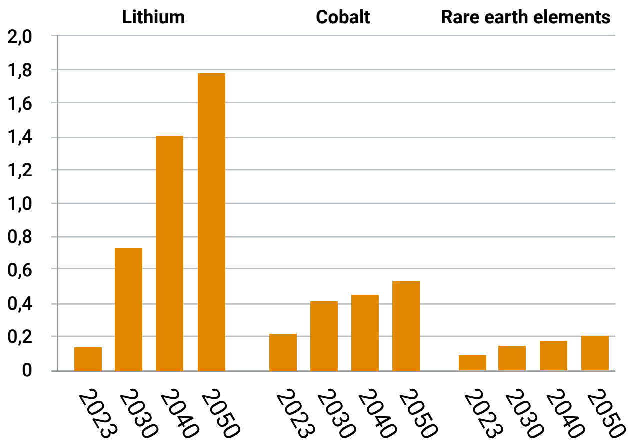


Figure 10 & 11: Global demand forecasts in million tons (Mt) of key minerals to reach net zero by 2050, 2023-2040[125].

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[121] European Commission, Critical raw materials - Internal Market, Industry, Entrepreneurship and SMEs
[122] IEA (2022) The role of critical minerals in clean energy transitions.
[123] European Commission (2021) Study on the resilience of critical supply chains for energy security and clean energy transition during and after the COVID-19 crisis.
[124] European Commission (2023) Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU. A foresight study.
[125] IEA (2024) Geographical distribution of mined or raw material production for key energy transition minerals in the base case 2023 2040.
[126] European Commission (2024) Critical Raw Materials Act
[127] European Commission (2025) Commission selects 47 Strategic projects to secure and diversify access to raw materials in the EU.
[128] European Commission, Selected strategic projects

Geographical distribution of mined or raw material production for key energy transition minerals in the base case, 2023-2040

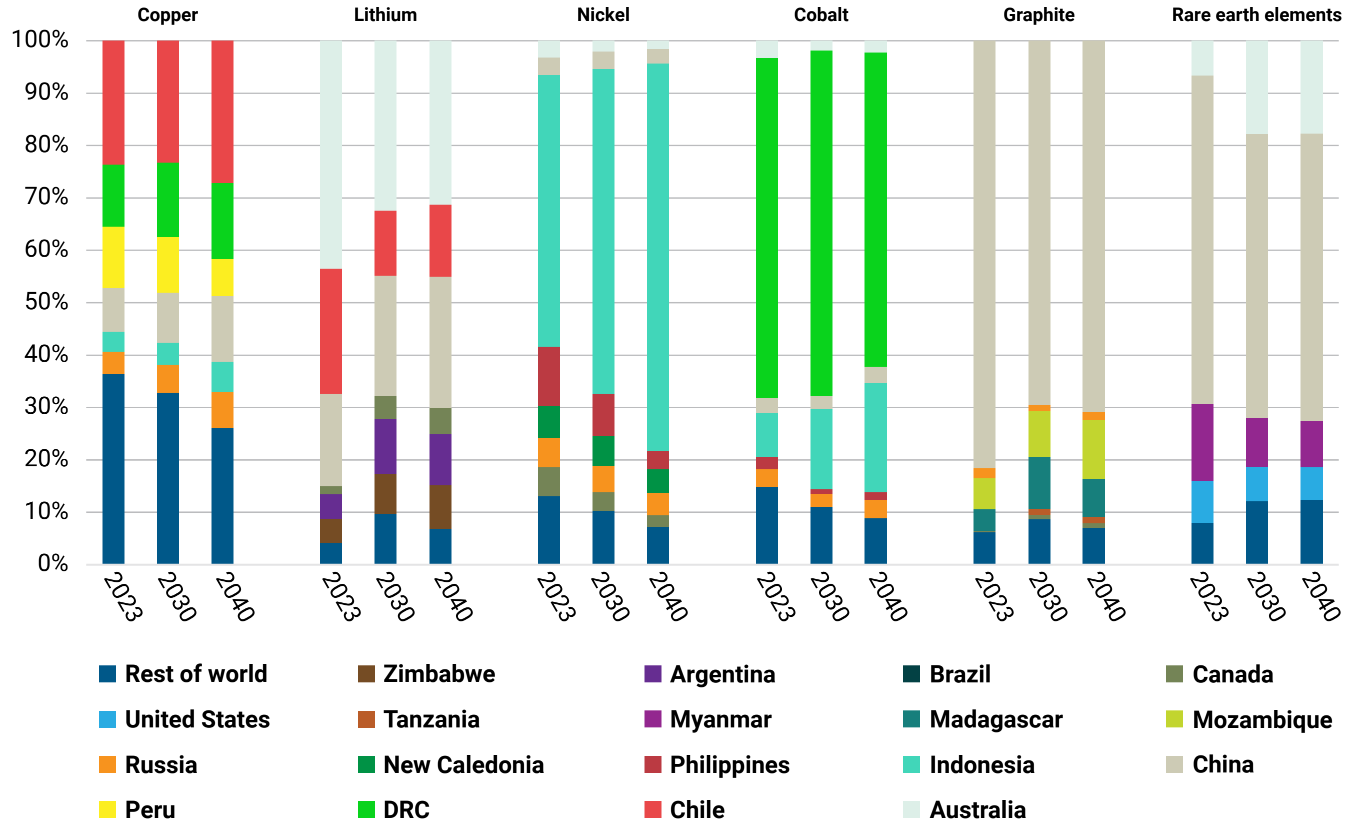

Figure 12: Geographical distribution of mined or raw material production for key energy transition minerals in the base case, 2023-2040[125].

Mining and quarrying activities generate over 500 Mt of waste annually in the EU, constituting 23% of the total EU produced waste[129]. When mining for minerals different types of mine waste are generally produced, including overburden (i.e., the soil and rock that is removed to access the ore body), waste rock (i.e., rock that is excavated during mining but does not contain sufficient minerals to be processed economically), tailings (i.e., the fine-grained waste material left after the valuable minerals have been extracted from the ore) and slag (i.e., impurities separated from the metal during refining). Today, overburden, waste rock, and slag are typically stored in large heaps or dumps near the mining site. Sometimes, they are used for backfilling mined-out areas or for land reclamation projects to restore the landscape. Additionally, these materials can be repurposed for construction, such as aggregate for roads or building foundations[130]. Tailings are often stored in heaps or in large ponds, which are engineered structures designed to contain the fine-grained waste material and prevent contamination of surrounding areas, surrounded by a dam. In some cases, tailings can be reclaimed by covering them with soil and vegetation to stabilise the area and prevent erosion.

Different greenhouse gas (GHG) emissions in the life cycle of mining

The mining industry's carbon footprint is significant and multifaceted, with emissions stemming from various stages of a mine's lifecycle. A major portion of these emissions comes from fossil fuel consumption used to power heavy machinery, transport materials, and process minerals. However, emissions also arise from specific chemical processes and the long-term impact of mining waste[131,132].

Production and operations

The majority of a mine's CO_2 emissions are generated during its operational phase, with on-site energy usage being the largest source of emissions. Mining operations require immense amounts of energy to run heavy-duty equipment like haul trucks, excavators, and drilling rigs. Furthermore, significant energy is consumed in mineral processing, which includes crushing, grinding, flotation, and smelting. This energy often comes from on-site combustion in machinery, power plants or the national grid, with fossil fuels being a major contributor. For coal mining specifically, additional emissions are present due to the presence of CH_4 within the layers of coal. This type of mining, however, is outside the scope of this paper.

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[129] Eurostat (2024) Waste statistics
[130] Note: It must be noted that their repurpose remains insufficient and lacks initiatives for large scale valuable applications.
[131] NetNada (2024) Reduce Carbon Emissions in the Mining Industry
[132] Climate portal (2020) Mining and Metals

Mining waste

Mining generates massive quantities of waste, primarily in the form of mine tailings and waste rock. These materials can contribute to greenhouse gas emissions in several ways:

- **Processing of mine tailings:** The crushing, grinding, transportation and froth flotation of mining waste is particularly energy intensive and requires the combustion of diesel and other fuels in on-site equipment used for managing and moving the large volumes of tailings.
- **Recarbonation of mine tailings:** Some mine tailings, particularly those from mafic and ultramafic rocks (rich in magnesium and calcium silicates), have the potential to absorb CO_2 from the atmosphere through a process called carbon mineralisation. When exposed to air and water, these silicate minerals react with atmospheric CO_2 to form stable carbonate minerals. This process can be a form of natural carbon capture and storage.

Carbon accounting of these emission streams

Carbon accounting for mining operations follows established methodologies from frameworks like the greenhouse gas (GHG) Protocol (for corporate reporting) and the United Nations Framework Convention on Climate Change (UNFCCC) (for national reporting). These systems categorize emissions to provide a clear and comprehensive GHG footprint.

The UNFCCC (which follows the Intergovernmental panel on climate change (IPCC) guidelines) includes the main aspects of mining through its guidelines on energy related emissions[133]. In addition, the chapter on metals industry emissions mentions several of the CRM listed by the EU (e.g. bauxite, coking coal, lithium, magnesium)[134].

The inclusion of the negative emissions, e.g. originating from the carbonation of mine tailings, is not yet fully incorporated into standard GHG accounting. The IPCC has recognized the need to account for CO_2 uptake in general but does not currently provide a clear basis to include it in a company's or national CO_2 emissions calculations. However, the IPCC is expected to provide a framework for its inclusion in its upcoming methodology report on CO_2 removal technologies, due in 2027[135,136].

In the GHG Protocol, scope 1 emissions are the direct emissions from sources owned or controlled by the mining company. They primarily include the combustion of fuels in on-site machinery and power generation. Scope 2 emissions involve indirect emissions from the generation of purchased electricity, heat, or steam used by the mine operator. All other indirect emissions in the value chain, including the production and transportation of purchased goods, employee commuting, and the emissions associated with the end-use of the mined products are categorized under scope 3 emissions.

It must be noted, however, that the GHG protocol is currently developing its "Land Sector and Removals Guidance" which provides companies with detailed rules for measuring and reporting GHG emissions and removals in GHG inventories specifically associated with, among other techniques, carbon dioxide removal technologies[137]. In the current draft, accounting requirements state that reporting removals is optional, and that companies need to separately account for removals based on their sink process (i.e. technological or biogenic sinks) and storage pool (i.e. land based storage, product storage, or geologic storage). Furthermore, the draft outlines specific requirements for GHG removals accounting such as: ongoing storage monitoring or traceability.

Building on these frameworks, the Science Based Targets initiative (SBTi)[138] allows companies to voluntarily validate near-term (5–10 year) and long-term targets, requiring often a reduction of 90 - 95% of scope 1, 2 and 3 GHG emissions by 2050. As specific sectoral guidance is not yet available for the mining sector, organizations in this field utilize the GHG Protocol as their primary tool for setting SBTI targets.

The opportunities for CDR in mine tailings management

Carbon mineralization of mine tailings

Ores containing valuable metals such as Nickel (Ni), Chromium (Cr), Platinum Group Elements (PGEs), and Cobalt (Co) are typically hosted within mafic and ultramafic rocks[139].

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[133] IPCC (2006) 2006 IPCC Guidelines for GHG Inventories – Energy
[134] IPCC (2019) Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories - Industrial Processes and Product Use – Metal Industry Emissions
[135] IPCC (2023) Climate Change 2023 Synthesis report
[136] MPA The concrete center, Concrete Carbonation & IPCC, Call for nomination of experts to Scoping Meeting for Methodology Report on Carbon Dioxide Removal Technologies and Carbon Capture Utilization and Storage & IPCC (2024) Expert meeting on CDR Technologies.
[137] GHG Protocol (2024) Land Sector and Removals Guidance
[138] Science based targets
[139] Mafic rocks, like basalt and gabbro, have moderate silica content and high magnesium (Mg) and iron (Fe) content, typically hosting copper (Cu) or iron (Fe) ores. Ultramafic rocks, such as peridotite, are characterized by low silica and high Mg and Fe content, typically hosting Ni, Cr, Co, and PGEs. Sources: Geologyn, Igneous Rocks Composition (Ultramafic, Mafic, Intermediate and Felsic) & Australian Government, Mafic ultramafic orthomagmatic mineral systems & Edward M.Riply and Chusi Li (2018) Chapter 3, Metallic Ore deposits associated with mafic to ultramafic igneous rocks)

When these rocks are processed for metal extraction, the resulting leftover mine tailings are rich in alkaline minerals containing divalent cations (Mg, Ca or Fe), such as olivine[140] ($(Mg,Fe)_2SiO_4$), serpentine ($(Mg, Fe)_3Si_2O_5(OH)_4$) pyroxene ($CaMgSi_2O_6$), chromite ($FeCr_2O_4$) and brucite ($Mg(OH)_2$)[141]. Based on these alkaline minerals, the mine tailings represent a significant opportunity for permanent CDR[142].

This potential for CO_2 sequestration is linked to the process of carbon mineralization, that permanently stores CO_2 by chemically binding it within the mineral matrix of the tailings[143]. This process is enabled because the leftover tailings still contain a high quantity of reactive silicate and hydroxide minerals. These minerals react with CO_2, essentially sequestering it. A simplified version of the mineralisation reaction is:

$$(Mg,Ca,Fe)_2SiO_4 + 2CO_2 \rightarrow 2(Mg,Ca,Fe)CO_3 + SiO_2$$

A key application of these reactions is enhanced carbon mineralization, which is the process in which the capacity of mine tailings to capture and permanently store atmospheric CO_2 is increased artificially. There are various techniques that enhance this process and differ in where the CO_2 reaction will take place (surficial or ex-situ) and what type of activation the minerals will receive to speed up the reaction. In surficial carbon mineralisation, typically the mine tailings react with the surrounded ambient CO_2 (in the air), whilst in an ex-situ configuration, often a concentrated CO_2 source is used in a closed reactor, either produced from biogenic origin or through direct air capture (DAC).

Other CDR opportunities of mining waste in other sectors

Due to the presence of various alkaline minerals in mining waste, they are also promising for generating CDR opportunities in other sectors, such as agriculture through enhanced rock weathering (e.g. AngloAmerican) and for oceans through ocean alkalinity enhancement. In both applications, dosing the mining waste will increase pH, which remediates potential acidity issues while at the same time locking atmospheric CO_2 into bicarbonates that remain permanently stored. In both applications, care should be taken that only mining waste is used, potentially after treatment, that is deemed safe for the environment. Although these CDR techniques warrant dedicated attention, they are **beyond the scope of this paper**.


CDR opportunities in the mining waste management sector

Rocks are mined and selected ores are extracted and refined.

Different types of mine waste are produced, including overburden, waste rock, tailings and slag.

Overburden, waste rock, slag, and (carbonated) tailings can be stored in heaps, or repurposed for backfilling, land reclamation and construction.

Mine tailings, which are rich in calcium and magnesium, offer a CDR opportunity by reacting with atmospheric or concentrated CO_2 to form stable carbonate minerals.

$$(Mg,Ca,Fe)_2SiO_4 + 2CO_2 \downarrow 2(Mg,Ca,Fe)CO_3 + SiO_2$$

Storage in heaps: Mine waste can be stored in heaps or large ponds and covered in vegetation to prevent erosion.

Backfilling: Mine waste can be used as filling materials for inactive mines.

Land reclamation: Mine waste can be used in land reclamation projects to restore the landscape.

Construction / Road construction: Mine waste can be used as a supplementary materials in concrete production or can be used in road construction.

Figure 13: CDR opportunity in the mining waste management sector.

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[140] Li et al. (2018), Integrated Mineral Carbonation of Ultramafic Mine Deposits—A Review

[141] Note: this list is non-exhaustive.

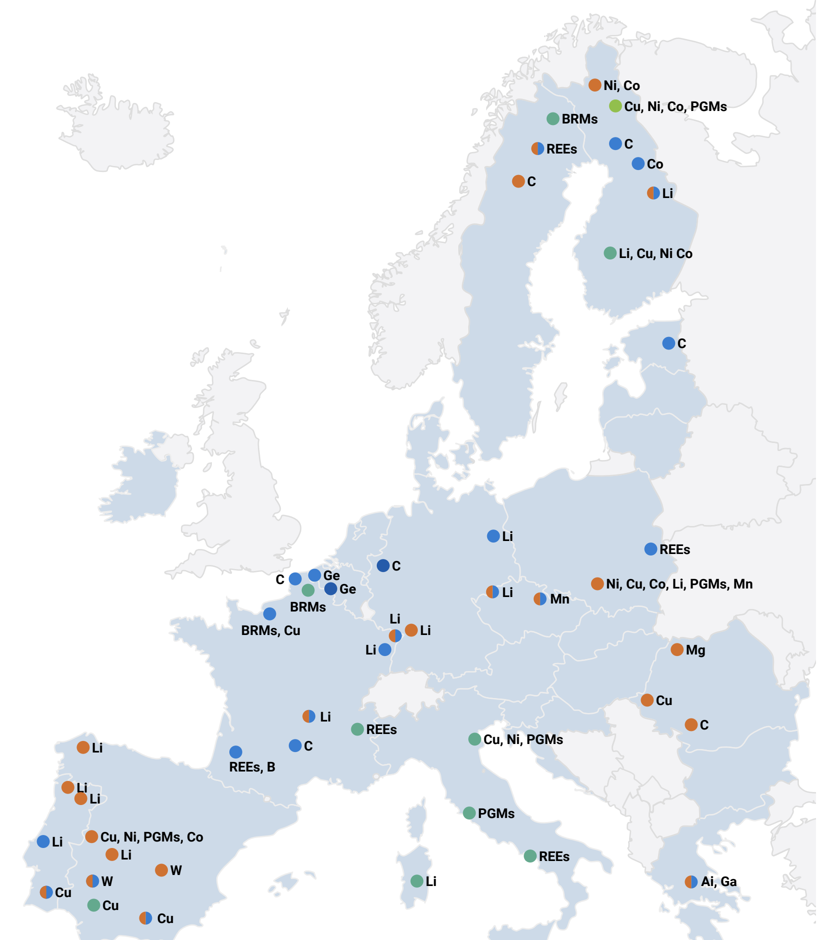
[142] IEAGHG (2022), Mineral Carbonation using Mine Tailings –A Strategic Overview of Potential and Opportunities

Al	Aluminium
B	Boron
BRMs	Battery Raw Materials[1]
Co	Cobalt
Cu	Copper
Ga	Gallium
Ge	Germanium
C	Graphite
Li	Lithium
Mg	Magnesium
Mn	Manganese
Ni	Nickel
PGMs	Platinum Group Metals
REEs	Rare Earth Elements
W	Tungsten

[1] Battery Raw Materials refer to lithium, cobalt, nickel, manganese and graphite.

Map Legend

Extraction
Processing
Recycling
Subsitution



Disclaimer: The location of projects is basedt on a regional scale and doesn't reflect their exact geographical locations

Figure 14: Strategic mining projects in the EU[151].

Potential scale of CDR in mine tailings management

Mine tailings exhibit wide variability in their mineral composition and therefore in their intrinsic carbonation potential, but nickel (Ni) and platinum group metal (PGM) tailings stand out as the most promising resources for CO_2 mineralization[143]. Their suitability reflects the high presence of reactive MgO and CaO minerals such as serpentine minerals (e.g. chrysotile, lizardite and antigorite); olivine minerals (e.g. forsterite) and hydroxides minerals (e.g. brucite)[144].

By 2030, Ni and PGM tailings have the potential to capture between 136 and 221 Mt of CO_2 annually through carbonation, depending on the different forecasted shared socio-economic pathways (SSP)[144,145]. This is linked to the production of 384 to 621 Mt Ni tailings and 53 to 89 Mt PGM tailings[146]. **By 2050, due to a higher expected demand for Ni and PGM metals linked to the production of clean energy technologies, this capacity increases to a range of 176 Mt up to 485 Mt of CO_2 per year.** By 2100, this could even rise to 255 Mt to as much as 1.32 Gt CO_2 per year, linked to a production of 723 to 3539 Mt Ni tailings and 93 to 849 Mt PGM tailings[147].

Moreover, beyond Ni and PGM tailings, in total 3 Gt of ultramafic and mafic tailings are currently already produced annually, which together with 28 Gt of legacy ultramafic and mafic waste that is still stored at mine sites, present substantial additional opportunity for carbonation[147].

Nevertheless, to fully reach this potential of CO_2 mineralization in mine tailings, the used technology has a significant impact, since this controls how much of the CO_2 can react with the active sites in tailings. The practical total potential for CO_2 mineralization in the mining sector is thus likely to be lower and will also depend on the **cost-effectiveness** of incorporating these technologies into current operations.

Specifically for the global nickel mining sector, achieving only a 10 wt% carbon capture rate in the tailings, compared to its potential of 25-37 wt%, already corresponds to the sequestration of approximately 35 Mt of CO_2, based on the Nickel production volumes of 2020[148]. With total global GHG scope 1 and 2 emissions from Nickel production in 2019 equal to 51 Mt of CO_2[149], this illustrates the significance of the CDR potential, through carbonation of mine tailings, to almost offset the sector's entire own GHG emissions.

As for the European Union, it already hosts more than 50 active non-

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[143] Milad Norouzpour et al. (2025) Activation methods for enhancing CO_2 mineralization via mine tailings-A critical review

[144] Phil Renforth (2019) The negative emission potential of alkaline materials

[145] Note SSP: shared socio-economic pathways are scenarios that project socio-economic changes up to 2100, as defined in the IPCC 6th assessment report on climate change. Key considerations include society's reliance on fossil fuel as well as challenges to mitigation and adaptation to climate change. SSP1 represents sustainable development; SSP2 middle-of-the-road development; SSP3 regional rivalry; SSP4 inequality and SSP5 fossil fuel development. Source: Climate Data Canada, Understanding shared socio evonomic pathways SSPs

[146] Renforth (2019) The negative emission potential of alkaline materials

[147] Arca et al. (2025) Beyond Extraction: Transforming mine waste into a net zero multibillion dollar opportunity

[148] Renforth (2019) The negative emission potential of alkaline materials

[149] Carbon chain (2024) Understand the emissions intensity of your nickel commodity

ferrous metal mining sites, several of which generate substantial volumes of mafic and ultramafic tailings with relevance for CO_2 mineralization[150]. These operations are concentrated in Poland, Finland, Sweden, Spain, Bulgaria, Ireland, Greece and Romania, though their production profiles vary significantly. Finland is by far the dominant source of EU nickel ore, which tailings have most potential for CO_2 mineralization, accounting for approximately 87% of all nickel mined within the Union. The remaining share is in Greece and Poland[151].

Moreover, 33 of the 47 strategic projects under the Critical Raw Materials Act (CRMA) are extraction focused, targeting battery and defence metals such as lithium (10), graphite (4), nickel (3), cobalt (3), copper (5), REE (3), and tungsten (3). Since some of these extraction projects include metals that will yield tailings with high carbonation potential, such as nickel, these EU-funded and supported sites present a major additional opportunity for CDR.

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[150] Scribd, 2024 Euromines mining for climate

[151] European Commission, Selected strategic projects

Deep Dive

Deep dive: carbon mineralisation of mining waste

Carbon mineralization is a natural process where mining waste, particularly that derived from mafic and ultramafic rocks, reacts with atmospheric CO_2. **By accelerating and optimizing this reaction, carbon dioxide can be permanently bound within the waste material, effectively turning it into a long-term carbon sink.**

Process design

The mineralisation of mafic and ultramafic mining waste can be achieved through various methods, which are generally categorized based on the source of CO_2 used (atmospheric vs. concentrated) and the location of the reaction (surficial vs. ex-situ). Below, several of the primary methodologies are listed:

01. Surficial mineralization

Surficial mineralization happens when crushed mined rocks or mine tailings, react with ambient CO_2[152]. One of the ways in which surficial mineralization with mining waste can be enhanced is by using autonomous rovers that churn the surface of a tailings pile continuously. This physical agitation constantly exposes new mineral surfaces to the atmospheric CO_2, thus boosting the rate of mineral carbonation and permanent CO_2 storage.

02. Ex-situ mineralization

Ex-situ mineralization focuses on accelerating the natural chemical reaction of CO_2 with the alkaline minerals within the mining waste. The overall procedure begins with the feedstock preparation, which often involves crushing the mine tailings or waste rock, to increase the reactive surface area of the material, a crucial step to enhance reaction kinetics. Next, the pre-treated waste is introduced into a closed reactor system. The reactor chamber has the advantage that a concentrated stream of CO_2 can be introduced, which further improves the reaction kinetics compared to using atmospheric CO_2. CO_2 Can be added as a gas (gas-solid carbonation) or dissolved in an aqueous solution (liquid-solid carbonation)[153]. Adding it in an aqueous solution is typically more reactive but also requires extra water management.

The reactivity of the mine tailings can also be further enhanced in the reactor chamber, e.g. by adding chemicals, stimulating mass transport, raising the temperature, increasing pressure or introducing high-intensity energy bursts to effectively activate the divalent cations in the mine tailing minerals, such as magnesium ions, to react with CO_2. These additional processes, however, also require energy or the production of chemicals, of which the required resources and the associated emissions should be carefully compared with their effectiveness in increasing the reactivity of the mineralization process.

The concentrated CO_2 can be sourced from an on-site biogenic point emitter, e.g. a biomass waste CHP or biogas upgrading plant, but can also be generated from atmospheric CO_2 by using a DAC technology[154]. For biogenic CO_2 producers that aim to store their CO_2, the proximity to a mine operator performing mineralization could result in **cost savings** by eliminating the need for expensive CO_2 transport and geological storage infrastructure.

At the end of the process, the resulting carbonated material is removed from the reactor. This process generates stable calcium and magnesium carbonates in the mining waste that can potentially be utilized as value-added products.

Economic perspectives

Capital investment

The initial capital expenditure can be substantial and varies significantly depending on the chosen mineralization approach (surficial or ex-situ) and the scale of deployment.

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[152] World Resources Institute (2023) 5 things to know about carbon mineralization

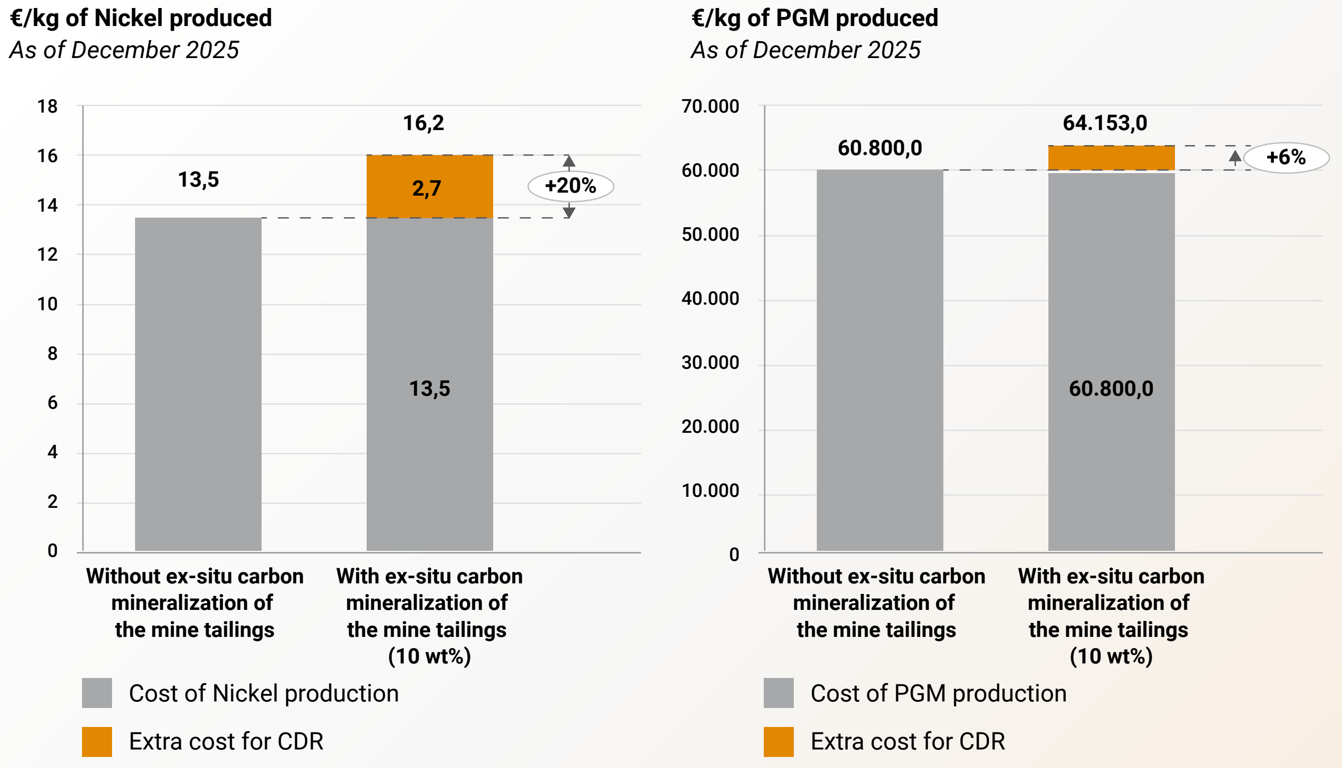
[153] Farzain Ud Din Kirmani et al. (2024) A holistic overview of the in-situ and ex-situ carbon mineralization: Methods, mechanisms, and technical challenges

[154] Michael Enemuo (2024) Transitioning the mining sector: A review of renewable energy integration and carbon footprint reduction strategies

- CAPEX for both methods:
    - **Crushing and sieving equipment:** A major cost factor is the acquisition of crushing machinery to process mine waste (rock or tailings) into the required smaller particle sizes, which is crucial for increasing the reactive surface area and enhancing reaction kinetics.
    - **Instrumentation and control systems:** Investments in sensors, monitoring equipment, and automated control systems are essential to ensure process optimization, efficiency, and safety. Dependent on the chosen process, these systems can regulate parameters like temperature, pressure, humidity, and CO_2 flow rates to maintain ideal reaction conditions.
- Additional CAPEX for surficial mineralisation
    - **Potential rovers/agitation equipment:** For active surficial methods, capital is needed for specialized autonomous rovers or heavy-duty equipment designed to continuously churn the surface of the tailings pile, exposing fresh mineral surfaces to atmospheric CO_2.
    - **Infrastructure for enhanced weathering** (if applicable): If the fine-ground material is to be applied elsewhere (e.g., agricultural fields, coastlines, as in ERW), investment is required for high-volume grinding mills and logistics infrastructure for large-scale transportation and spreading.
- Additional CAPEX for ex-situ mineralisation
    - **Reactor/chamber system:** The core investment for ex-situ processes is the closed reactor or chamber system capable to handle the mining waste and withstanding the necessary operating conditions (e.g., high pressure, high temperature) for accelerated carbonation.
    - **Gas handling and storage:** A system for sourcing, storing, and delivering a high-concentration stream of CO_2 is essential. This includes gas storage tanks, compressors, and specialized piping infrastructure, especially if the CO_2 is sourced from a point emitter or Direct Air Capture (DAC) unit. The cost of integrating DAC systems, which are currently energy-intensive and have high CAPEX, is a significant barrier.

Operational investment

- **Energy consumption:** A primary OPEX is the energy consumption associated with: operating the crushing and sieving equipment, running the reactor system (e.g., heating, pressurizing), operating the CO_2 compressors and handling systems, especially in ex-situ processes or for utilizing chemicals or high-intensity energy bursts to activate the minerals.



€/kg of Nickel produced
As of December 2025

€/kg of PGM produced
As of December 2025

Figure 15 & 16: Costs of Nickel and Platinum Group Metal production with, and without implementing carbon mineralization technology at a rate of 10 wt% in the mined tailings waste products[161]

- **Cost of CO_2 for ex-situ mineralisation:** For ex-situ mineralization, the cost of sourcing, capturing, or transporting the concentrated CO_2 stream is a critical factor. The cost can be lower if integrated with an on-site biogenic point emitter, e.g. a biomass waste CHP or biogas upgrading plant, but higher if starting from a non-concentrated CO_2 supply, such as with DAC technology.

- **Maintenance and labor**: Regular maintenance of heavy machinery (crushers, rovers, reactors, compressors) is a continuous cost. Additionally, skilled labor is required to operate the sophisticated equipment, monitor the chemical process, and manage the logistics of waste intake and product output.

Impact on the current cost of production

When considering that a Nickel producer would reach a carbon capture rate of 10 wt% in its Nickel tailings, our analysis shows that this would result in an additional cost increase of around €2.69 per kilogram of Nickel[155]. This reflects a 20% increase compared to the current metal price[156], but does not yet take into account any additional revenues or cost savings created by installing CO_2 mineralization in the plant. Also, future CDR technology improvements could further bring down this cost.

When looking at an end-product, for example a NMC battery, a product that even contains up to 9% of its total weight in Nickel[157], the costs associated to Nickel are less than 20%[158], so for this product the price increase of CO_2 mineralization would be less than 6%.

For platinum group metals (PGM) tailings, also considering a carbon capture rate of 10 wt% in all tailings produced, would increase the cost by €3354 per kilogram of metal extracted according to our analysis[159]. **Comparing to current PGM market prices, this reflects a production cost increase of 5.6% in both scenarios[160],** also not yet considering any additional revenues or cost savings created by installing CO_2 mineralization in the plant.

Potential cost savings & revenues

The economic case for carbon mineralization is dependent on its potential to transform the required costs into revenue streams.

- **Stabilization and neutralization:** The process has the potential to transform reactive, often unstable mine tailings into more geochemically stable, solid carbonates. This can reduce the long-term environmental liability and monitoring costs associated with acid mine drainage (AMD) and tailings storage facility (TSF) management and closure.

- **Reduced storage footprint:** Converting a portion of the tailings into a stable, value-added product can potentially reduce the volume of waste requiring long-term containment, lowering closure and post-closure maintenance costs for TSFs.

- **Revenue generation with carbon credits:** The permanent sequestration of CO_2 is a form of CDR that can be verified, quantified, and sold in voluntary or compliance carbon markets. The revenue generated from carbon credits (e.g., per tonne of CO_2 sequestered) can be a primary revenue stream, particularly as carbon prices rise.

Pioneer projects:

Arca was founded in 2021 to leverage mining waste for industrial-scale carbon removal. Built on over 20 years of academic research, field trials, and collaborations with more than 30 mining companies worldwide, Arca's technologies accelerate the natural process of carbon mineralization in mining wastes that contain magnesium–rich minerals like brucite and serpentine. In a first step, Arca's mineral activation technology uses high–intensity energy bursts to liberate the magnesium, which makes the tailings more reactive to CO_2, therefore increasing the natural ability of ultramafic rock to capture and permanently store CO_2. In a second step, rovers further increase mineralisation, churning the surface of the tailings to expose fresh rock to atmospheric CO_2. Arca estimates that up to 200 kg of atmospheric CO_2 can be captured and stored per tonne of tailings. Arca is currently undertaking two main projects on-site. The Mt. Keith demonstration pilot, launched in November 2023 with BHP, was the world's first carbon mineralization project on an active mine site, successfully testing Smart Churning (surficial mineralization) and Measurement, Reporting, and Verification (MRV) technologies to safely remove atmospheric CO_2 while integrating seamlessly into the mine's operations. Separately, the Carbon Sandbox Project in British Columbia is pioneering advanced MRV methodologies to build confidence in this climate solution. This dedicated testing site focuses on developing a highly accurate, four-measurement quantification method and a robust algorithm for real-time monitoring of the carbon exchange between air and rock.[161]

Similar to Arca, Exterra Carbon Solutions was founded in 2021 to leverage legacy and operational mine tailings for industrial-scale carbon removal and critical mineral production. The company's core technology, engineered mineral carbonation, uses a two-step process: the LOW (Low-carbon Oxide from Waste) process extracts high-purity alkaline metal oxides (like magnesium oxide) and valuable co-products (such as nickel) from mine waste; then, the ROC (Reactive Oxide to Carbonate) process utilizes these oxides to rapidly and permanently mineralize captured CO_2 into rock. Exterra has derisked its solution through pre-commercial pilot operations in Val-des-Sources, Quebec.

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[155] Renforth (2019) The negative emission potential of alkaline materials
[156] GlobalTrackDashboard (2025) Nickel Price in Euro Member Countries per Kilogram - Real-Time Nickel Tracker
[157] Storage Lab Raw material cost | Storage Lab
[158] Battery Design NMC vs LFP Costs - Battery Design
[159] CO_2 Value Europe (2024) Exploring CO_2 Mineralisation: a scalable path to net-negative emissions
[160] BullionByPost (2025) Live Platinum Price in EUR per Kilogram
[161] Note: This analysis is based on data from The Negative Emission Potential of Alkaline Materials (Nature Communications) regarding nickel (Ni) and platinum group metals (PGM) tailings production, extraction rates, and carbonation capture efficiencies. Cost estimates for ex situ mineralisation are sourced from Exploring CO_2 Mineralisation: A Scalable Path to Net-Negative Emissions (CO_2 Value Europe), assuming a carbon capture cost of €189 per tonne of CO_2. Current market prices used for reference are €13.50 per kilogram of nickel (Nickel Price in Euro Member Countries per Kilogram – Real-Time Nickel Tracker) and €60,486 per kilogram for PGMs (Live Platinum Price in € per Kilogram).

Conclusions and limitations

While the theoretical CO_2 sequestration capacity of ultramafic mine waste is vast, i.e. more than 100 Mt per year from new tailings alone, embedding CDR into the global mining sector faces significant challenges. The implementation of carbon mineralization technologies often requires substantial upfront investment and operational energy, which can be difficult to justify without guaranteed long-term revenue streams. This section explores the core challenges that must be overcome for companies to implement carbon mineralization:

- **Non-inclusion in carbon accounting methods:** The absence of an IPCC-set accounting framework for CDR in the mining sector can be regarded as the main barrier to implementing this technology. This regulatory void prevents the quantification of sequestered CO_2 and the inclusion of potential valorisation (value-added products) in financial reporting, thereby preventing the primary revenue stream from carbon markets (e.g., carbon tax or ETS compliance).

- **Absence of mandatory policies and direct incentives:** Current environmental and mining regulations generally do not mandate the use of CDR technologies for mine waste management, nor do they often include direct financial incentives (beyond potential carbon market access) to offset the implementation costs. This means that mining operators are not legally obliged to adopt these technologies and, due to the absence of a clear financial imperative or legislative push, they will naturally favour less expensive, existing waste management methods that meet minimum compliance standards, slowing the essential transition towards sustainable practices.

- **Current low technology readiness level (TRL):** The scalability of the technology to handle large volumes of material is unproven for the time being. The TRL for deploying mine waste mineralisation technology varies depending on the specific technology. The churning of mine tailings has reached TRL 8, signifying that it is ready for field deployment and can be implemented under real-world conditions. In contrast, mineral activation technology is at TRL 4, indicating that it is still in the laboratory stage and requires further development before it can be utilised on large scale.

- **Price sensitivity of the sector:** The mining industry's tight margins put a limit on expensive processes that have long ROI durations. The implementation of enhanced mineralization technologies must compete directly with cheaper, conventional waste disposal, which currently carries lower financial liability.

- **Public acceptance:** Even with verified CO_2 removal, projects face resistance regarding land-use, noise, and visual impact. New industrial infrastructure and the expansion or modification of waste facilities require a social license to operate that can be rapidly withdrawn if local communities perceive any risk to health, safety, or environmental integrity. This resistance often translates into lengthy and unpredictable permitting delays.

The proposed policy recommendations to address these challenges are covered in the next chapter.

Policy recommendations and conclusion

The previous sections examined the potential for carbon dioxide removal (CDR) technologies across three sectors: wastewater treatment, concrete recycling, and mining waste management. For each sector, the analysis included an overview of the different available CDR technologies, the CDR potential, an economic assessment and an illustration of real-world examples. It became clear that these three sectors have a lot of potential for large scale integration of CDR technologies, but that they also face limitations to scale up fast.

In this section, we begin with a summary of the key limitations that were identified across the three sectors. We then present a series of policy recommendations to address these identified challenges. The policy recommendations have been divided in two distinct parts. On the one hand, **facilitating measures** are presented, that can help to make CDR technologies more mature or contribute to the business case for deploying CDR technologies. On the other hand, **embedded CDR policy recommendations** are presented, sector tailored, that can guarantee the scale up of CDR technologies, by mandating a minimum uptake of CDR technologies, either via policies, standards or public procurement.

Main limitations to the scaling up of CDR technologies

01. **Knowledge gaps:** CDR technologies directly contribute to reducing greenhouse gas (GHG) emissions but may also provide other co-benefits. Today, these different positive impacts have not been fully mapped. Setting up clear research priorities are important to unravel all the existing fundamental knowledge gaps. This lack of fundamental, but also technical and practical knowledge prevents policymakers and companies from accurately estimating the GHG emissions that are released in these sectors and how CDR technologies could contribute to reducing these emissions, in addition to other co-benefits they may provide.

02. **Incomplete or inaccurate GHG emissions inventories:** Based on the still existing knowledge gap in GHG emissions, current GHG emissions inventories and accounting frameworks, such as the GHG Protocol and those used by the United Nations Framework Convention on Climate Change (UNFCCC), are also incomplete for accurately recognizing and reporting all the positive contributions CDR technologies yield in reducing GHG emissions. These accounting limitations limit the recognition of CDR efforts and their climate benefits.

03. **Few pilots and FOAK projects:** The full potential benefits and the associated costs of CDR technologies only become clear when setting up pilot and first-of-a-kind (FOAK) projects. By guaranteeing the iterative establishment of different pilot and FOAK projects, continuous improvement of CDR technologies can be made possible, maximizing their benefits and lowering the financial impact. In the sectors observed, pilot and FOAK projects are already being developed, but often based on support originating from the voluntary market scheme or private investments. A higher public support would make these businesses more durable and allow them to faster scale up and becoming technology leaders in the countries where they are supported.

04. **Lack of willingness from end-users to pay for the premium price voluntarily:** If not mandated, many end-users are not willing to pay a premium price for products that have a lower GHG footprint, limiting the market demand. On top of this, the low-carbon labelling of products is not always well established as well as incentives that are linked to it. Even when it is mandated, pushing higher costs to consumers can be politically sensitive.

05. **Absence of policies mandating the uptake of CDR technologies:** The absence of CDR policy mandates, combined with difficult business cases for CDR technologies to earn back the investments, results in slow deployment of CDR technologies. This is particularly relevant to the sectors covered in this report, of which the companies and their activities are not included by schemes putting a price on GHG emissions.

06. **Limited CO_2 infrastructure:** Many of the CDR technologies explored in this study may benefit from an already existing CO_2 infrastructure, that could easily connect atmospheric or biogenic CO_2 sources (such as biogenic CO_2 produced from wastewater treatment) with storage technologies (such as the mineralization reactions). The need for building up this infrastructure prior to implementing a new CDR technology also drives up costs.

Policy recommendations

To address the limitations above, this section includes first an overview of **facilitating policy measures** that could boost the uptake of CDR technologies and afterwards an overview of measures to embed CDR requirements in policies. The facilitating measures include and are explained in detail below both on a cross-sectoral level as well as on a sector specific level:

- Raise the knowledge maturity of CDR technologies to foster science-based decision making

- Provide sufficient dedicated funding to set-up pilot and FOAK CDR projects for advancing the technology maturity and scale

- Perform monitoring and reporting on all GHG emissions in the different GHG accounting methodologies

- Include the sector-specific CDR technologies in the different CDR purchasing vehicles, especially in the policy-driven schemes

The embedded CDR policy recommendations have as a main advantage that they can guarantee a chosen level for CDR technologies adoption, even without the need for public subsidies. As shown in the previous sections, the adoption of CDR technologies will have a minimal impact on the price to consumers, whilst having the potential to completely decarbonise the corresponding waste management sectors and even offsetting emissions of other sectors. Embedded CDR policy requirements could be included via mandates, standards and public procurement. They are explained in detail below, after the facilitating policy measures, on a sector specific level.

Facilitating policy measures

Raise the knowledge maturity of CDR technologies to foster science-based decision making

Overview

To overcome the knowledge gap limitations for the deployment of CDR technologies and accelerate the market readiness of CDR technologies, governments must address existing research gaps. Policy makers such as the EU under Horizon Europe, could establish clear research priorities to close fundamental knowledge gaps both on GHG emissions as well as additional co-benefits. Closing knowledge gaps on GHG emissions could subsequently directly feed the establishment of holistic GHG reporting methodologies by deriving plant specific emission factors. Closing knowledge gaps on the additional co-benefits could further improve the business case of deploying CDR technologies, by showcasing the full range of benefits they yield.

Sector specificities

Wastewater treatment

Research priorities should focus on:

- Obtaining a clear fundamental understanding of all the different GHG emissions (N_2O, CH_4, biogenic CO_2 and fossil CO_2) that are produced in the different stages of conventional wastewater treatment plants.

- Building a database, that could become part of the European innovation centre for industrial transformation and emissions (INCITE), containing updated techno-economic evaluations (TEA) and life cycle assessments (LCA) of promising CDR technologies for wastewater treatment plants (WWTPs), including their impact on:
    - All GHG emissions, including N_2O and CH_4, next to CO_2 emissions;
    - Environmental co-benefits, such as increasing the alkalinity of rivers and oceans, or their impact on phosphorus or nitrogen removal; and
    - Human health co-benefits, such as their potential in long-lasting chemicals removal.

GHG emissions
CO_2 emissions that are produced during wastewater treatment, are often reported to be of 100% biogenic origin, although part of these emissions can also have a fossil origin (approx. 10%). CDR technologies may also have an impact on other GHG emissions (N_2O and CH_4), e.g. by impacting N_2O and CH_4 formation during secondary treatment.

Environmental co-benefits
Besides their positive impact on GHG emissions, CDR technologies may also provide other environmental co-benefits that are important to further clarify. As an example, wastewater liming will not only store CO_2 permanently in bicarbonates but will also increase the overall alkalinity of the wastewater. After disposal, this can contribute to the total alkalinity level of rivers and oceans, that are becoming more acidic due the increasing levels of atmospheric CO_2.

Since acidity issues in rivers and oceans can occur all over Europe, and it is expected to become even more important to monitor due to enhanced atmospheric CO_2 levels, it is recommended for the EU to host a knowledge sharing platform, which could be called 'the Alkalinity Atlas'. This platform could bring together all data that is available on pH monitoring in rivers and oceans, as well as all processes that impact pH levels, such as wastewater treatment plants, agriculture, industrial emissions, etc. Next to data visualizations, the platform could also bring together all prominent stakeholders to engage on the topic and find solutions to bring back pH levels within safe environmental limits. This will not only foster the biodiversity but also provide resilience for agricultural and maritime activities.

Human health co-benefits
Wastewater treatment also yields benefits for human health. Next to reducing phosphorus and nitrogen levels, it can also reduce long-lasting chemicals that are present in the wastewater, such as PFAS. As an example, the use of pyrolysis can convert PFAS and render it harmless. It is therefore recommended to monitor and consider all potential co-benefits of these CDR technologies, e.g. when providing funding for research or pilot projects.

Concrete recycling

Research priorities should focus on:

- Obtaining a clear fundamental understanding on the CO_2 emissions that are captured in concrete, both during it lifecycle as well as when it becomes waste

- Building a database, that could become part of INCITE, containing updated TEA and LCA of promising CDR technologies for concrete recycling, including their impact on:
    - CO_2 emissions; and
    - Performance co-benefits, such as improved material properties.

GHG emissions
To demonstrate the total impact of enhanced carbonation on capturing CO_2 emissions in concrete waste, it is important to achieve a clear fundamental and technical understanding of how much emissions can be captured additionally, compared to concrete waste that is recycled without enhanced carbonation treatment.

Performance co-benefits
Today, many policies and technical standards limit the use of recycled aggregates in new building materials. Performing additional research on the maximum amount of recycled aggregates, before and after carbonation, that can be added to new building materials, is imperative to stimulate the circular economy.

Mining waste management

Research priorities should focus on:

- Obtaining a clear fundamental understanding of the CO_2 emissions that are captured in mining waste

- Building a database, that could become part of INCITE, containing updated TEA and LCA of promising CDR technologies for mine waste management, including their impact on:
    - CO_2 emissions; and
    - Environmental co-benefits, such as tackling acid mine drainage (AMD) or improving soil quality.

GHG emissions
While the sequestration of atmospheric CO_2 linked to mineral carbonation has been recognised as a natural process in official greenhouse gases inventories such as the IPCCC framework, their potential as an enhanced CDR technique has not yet been accounted for. This highlights a clear research gap questioning how CDR technologies such as enhanced mineral carbonation can be quantified, optimized and scaled in a cost-effective way across the mining sector to deliver measurable reductions in GHG emissions[162].

Environmental co-benefits
Beyond their positive contribution to GHG reduction, CDR technologies applied in the mining sector can also deliver significant environmental co-benefits.

A typical environmental concern linked to mining waste is AMD, a major issue resulting from the oxidation of sulfide minerals by water and oxygen, which creates highly acidic soil and water leading in addition to the indirect release of heavy metals such as Pb, Cu, Zn, Cd and As into the environment[163,164]. The materials that cause AMD could be treated ex-situ in a controlled environment, potentially in the same reactor used for CO_2 mineralization, saving on capital expenses. For instance, a potential solution for handling AMD is the addition of alkaline materials, such as quicklime (CaO), which could potentially also further enhance the CO_2 capture. Furthermore, the use of this controlled ex-situ reactor could also result in the production of useful new materials from the mining waste. Pioneer projects like Exterra Carbon solutions demonstrate how products generated during mineral carbonation can be used in other sectors such as the construction or automobile sector[165].

Another potential co-benefit is the use of the alkaline mine tailings for soil improvement, through enhanced weathering, which also results in the storage of atmospheric CO_2. Indeed, their capacity to alkalinize the soil as described above increases the cation exchange capacity (CEC) which allows the soil to retain amongst others, essential nutrients for optimal plant growth such as Mg, Ca, K or P, while also reducing nitrous oxide N_2O emissions[166]. The latter occurs as alkaline pH promotes the enzymatic conversion of nitrite to dinitrogen, a harmless component[167]. However, for soil improvement, careful environmental assessment and management are essential, since mine tailings may contain toxic elements. Therefore, ongoing monitoring and site-specific assessments will be essential to guarantee that only mine tailings are used that are deemed safe for the environment and human health.

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[162] IPCC (2019) 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories
[163] Augusto Vaghetti Luchese et al. (2023) Use of quarry waste basalt rock powder as a soil remineralizer to grow soybean and maize
[164] Hamid Radfarnia (2024) Accelerated CO_2 Mineralization of Acid Mine Drainage assisted by an ultrasound technique: an experimental parametric study
[165] Cision (2025) Exterra Carbon Solutions Raises $20M Series A to Transform Mining Waste into Low-Carbon Critical Minerals & CO_2 Sequestration
[166] Xavier Dupla et al. (2024) Let the dust settle: Impact of enhanced rock weathering on soil biological, physical, and geochemical fertility
[167] Isabella Chiavaralloti et al. (2023) Mitigation of soil nitrous oxide emissions during maize production with basalt amendments

Provide sufficient dedicated funding to set-up pilot and FOAK CDR projects for advancing the technology maturity and scale

Overview

To tackle the challenge of insufficient funding for pilot and FOAK projects with high upfront costs, a blended finance strategy is crucial for advancing CDR projects through maturity and scaling phases. In Europe, immediate implementation is possible by allocating dedicated resources within existing research and innovation programmes, including Horizon Europe (incl. European Innovation Council), the Innovation Fund, and the forthcoming European Competitiveness Fund. Ideally, this would involve establishing a dedicated Horizon Europe destination for CDR technologies, closely coordinated with the Competitiveness Fund to ensure seamless support through scale-up phases. Additionally, member states and municipalities can contribute funding to pilot projects, positioning themselves as technology leaders while advancing their CO_2 storage capabilities to meet GHG emission targets.

Once CDR technologies mature and become commercially viable, for example through higher market prices or revenues from carbon credits, public-backed loans, even without subsidies, may be sufficient to support large-scale deployment.

Providing this funding would contribute to the continuous improvement of CDR technologies and could help position the EU as a technology frontrunner, potentially strengthening the region's competitiveness.

Sector specificities

Wastewater treatment

Most CDR technologies for the wastewater treatment sector are not yet deployed at a large scale but rather in a few plants at a pilot level. To advance these technologies and bring down costs by scaling up, it is recommended to provide sufficient public funding to speed up the setting up of these initial pilots and FOAK large installations. The required funding will differ on the type of technology and the size of the WWTP. The implementation of most technologies could benefit of dedicated public capital expenditures (Capex) support in the form of grants with a size of **0.2 – 1 million EUR per project**, combined with private financing or public backed loans (e.g. blended financing) to reach final investment decisions (FID). Many of the technologies also have a clear operational expenditures (OPEX) component, for which additional support could reduce risks.

Concrete recycling

Carbonation CDR technologies for concrete waste have recently achieved pilot level stage, but only for a limited number of countries. The technologies used in these first pilots can also further advance to bring down costs and increase the CO_2 uptake. Hence, it is recommended to provide sufficient public funding to speed up the setting up of these initial pilots and FOAK large installations. Dependent on the size of the concrete recycling plant, the implementation of carbonation CDR technologies could benefit of dedicated public CAPEX support in the form of grants with a size of **0.4 – 2 million EUR per project** , combined with private financing or public backed loans (e.g. blended financing) to reach FID. This technology also has a clear OPEX component, for which additional support could reduce risks.

Mining waste management

While technical and research challenges for enhanced rock mineralization must be addressed to move from CDR in the mining sector from pilot to commercial scale, the primary barrier to global scale up remains cost[168]. Dependent on the size of the mining plant, the implementation of carbonation CDR technologies could benefit of dedicated public CAPEX support in the form of grants with a size of **1 – 5 million EUR per project**, combined with private financing or public backed loans (e.g. blended financing) to reach FID. This technology also has a clear OPEX component, for which additional support could reduce risks.

Perform monitoring and reporting on all GHG emissions in the different GHG accounting methodologies

Overview

Future revisions to GHG emission accounting methodologies (at the national and company level) must ensure that all positive GHG contributions achieved by CDR technologies, are accurately recognized and reported. This will give clear incentives to increase the associated negative GHG emissions originating from CDR technologies on a national, local as well as on a corporate level (scope 1), especially if it is also considered in the scope 3 emissions of other companies that buy products from sectors including CDR technologies.

In this context, low-carbon labelling of raw materials that reflects the reduced CO_2 intensity achieved through CDR can become increasingly important, especially as the EU and other regions are starting to implement carbon border adjustment mechanisms (CBAM). CBAM will consider the CO_2 embedded emissions of materials for tax provisions at a cross-border level. As soon as new materials, linked to the sectors in this study, would become part of a CBAM, inclusion of performed CDR activities in their CO_2 labelling could help companies demonstrate the lower carbon footprint of their products, facilitating market access and potentially reducing CBAM-related costs or tariffs.

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[168] Climate Science, risks & solutions (2024) Enhanced Rock Weathering

Sector specificities

Wastewater treatment

In GHG emission inventories (e.g. GHG protocol & UNFCCC), the biogenic CO_2 emissions released during wastewater treatment are often not reported on, and thus monitored, since these emissions originally were derived from biomass. Consequently, additional storage of these emissions might also not be counted for. This is especially true when the CO_2 is not separately collected and stored, as is the case for BECCS, but kept in the water, as is the case for wastewater liming.

On top of this, not all CO_2 emissions produced in the wastewater treatment process are of biogenic origin, a smaller amount will be originating from fossil origin. Some CDR technologies may also have a positive impact on the other produced GHG emissions (N_2O and CH_4) in WWTP.

Concrete recycling

In GHG emission inventories (e.g. GHG protocol & UNFCCC), the storage of CO_2 emissions via concrete carbonation is often not reported on and thus monitored. Consequently, additional storage of these emissions might also not be counted for.

Mining waste management

In the existing GHG emission inventories, while mineral carbonation is acknowledged as a chemical process absorbing CO_2, it is often not reported on and thus monitored. Consequently, additional storage of these emissions might also not be counted for.

Include the sector-specific CDR technologies in the different CDR purchasing vehicles, especially in the policy-driven schemes

Overview

The additional CO_2 storage capacity generated in the wastewater treatment, concrete recycling or mining waste management sectors could be of interest to other sectors that face greater difficulty in achieving climate neutrality. This cross-sectoral interest could generate private financing to support sectors that are deploying CDR technologies and are becoming net negative.

Already today, voluntary markets exist for carbon credits, where companies can buy carbon credits to offset their emissions. These carbon credit schemes are based on detailed certification processes to guarantee that the carbon credits truly represent the associated stored CO_2 emissions compared to the baseline, and subtracting any associated emissions of the CDR technology.

Europe is building its own certification registry based on the carbon removals and carbon farming (CRCF) Regulation. At this stage, the certification processes are still being built, and the sale of carbon units is yet to be started. To provide incentives on the short-term for the scaling-up of CDR technologies in the explored sectors from these different CDR purchasing vehicles, it is recommended to guarantee that the certification processes are set-up with priority to make sure that these technologies are directly integrated. When the purchasing program is set up, it is recommended to also support these novel forms of CDR to foster maturity and technology cost decreases. This can be achieved by applying a portfolio approach to the purchases, which will spread risks and costs, incentivize innovation, and support decarbonization across multiple sectors.

Embedded CDR policymaking

Wastewater treatment

Current policy landscape

Most nations have strict regulations on how wastewater should be treated with the primary aim of safeguarding public health and the environment. Central to these regulations are rules, which lay down the minimum requirements for the collection, treatment, and discharge of wastewater.

In the EU, two main regulations are applicable:

- The **Water Framework Directive**, which requires Member States to protect and, where necessary, restore water bodies (i.e., rivers, lakes, and groundwater) so that good chemical and ecological status is achieved, and deterioration is prevented[169].
- The revised **Urban Wastewater Treatment Directive**, which outlines the requirements for the collection, treatment, and discharge of wastewater[170].

These EU rules are supplemented by national frameworks, which interpret and adapt the EU Directives to ensure alignment within the national context. Member States can go beyond the minimum requirements (e.g., more stringent deadlines or thresholds, imposing additional requirements, etc.). Additionally, municipal rules further refine these requirements (e.g., through concession granting and permitting procedures) to address local specificities and objectives (e.g., such as human health, environmental protection, or climate action).

Installing mandates

This paper recommends that the already established regulatory framework of the EU's wastewater treatment sector could be amended

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[169] Offical Journal of the European Communities (2000) DIRECTIVE 2000/60/EC
[170] Offical Journal of the European Union (2024) DIRECTIVE (EU) 2024/3019

to mandate a minimum level of CDR, which would then be automatically transposed to the different member states.

The revised EU Urban Wastewater Treatment Directive, for example, already mandates urban wastewater treatment plants (of 10 000 p.e. and above) to reach energy neutrality at a national level by 31 December 2045. Moreover, these urban wastewater treatment plants are also mandated to set up a data set containing information on the GHG emissions, including at least CO_2, CH_4 and N_2O, by 31 December 2030. For the measuring, estimating and modelling of the direct and indirect GHG emissions from urban wastewater treatment plants, the Commission is empowered to adopt an implementing act by 2 July 2027.

Within this adoption of the implementing act, it is recommended for the Commission to include the mandatory monitoring of biogenic CO_2 released by wastewater treatment plants, as well as the stored biogenic CO_2 emissions from implemented CDR technologies.

Based on this monitoring of GHG emissions, and as a next step on top of the energy neutrality obligation, future amendments of the Urban Wastewater Treatment Directive could mandate a minimum amount of CDR from wastewater treatment plants, based on proven mature and cost-efficient CDR technologies that do not significantly harm, but rather generate co-benefits for the environment, human health and the wastewater treatment processes.

This could be achieved by installing a climate neutrality goal, or even a net negative target on GHG emissions in the wastewater treatment sector, on top of the energy neutrality goal by 31 December 2045. This could be linked to the overall 2050 climate neutrality goal set forward by the EU. **Achieving net negative GHG emissions in the wastewater treatment sector is technically and economically feasible and will contribute to offsetting net positive emissions in other sectors that have more difficulty to reach net zero and that face international competition.**

Before launching this new GHG emission target for the wastewater treatment sector, the Commission could already reward frontrunners that are investing in CDR technologies by introducing an offset methodology in the implementing act for the energy neutrality goal. This could, e.g. allow national governments that do not reach the energy neutrality objectives, to also allow the purchase of energy in relation to the amount of GHG emissions reduced by CDR technologies installed in WWTP. This amount can be made variable depending on the coupled GHG emissions of the energy purchased.

Concrete recycling

Current policy landscape

The regulatory framework of the EU's concrete recycling sector aims to ensure that concrete waste is managed in a way that minimizes environmental impact, promotes recycling and reuse, and supports the transition to a circular economy. Central to this framework are:

- The **Waste Framework Directive**, which establishes the foundational principles and regulations for waste management within the EU[171]. It notably required Member States to increase the share of C&DW, including concrete, being prepared for reuse, recycled, or recovered, including backfilling, to a minimum of 70% by weight by 2020[172].
- The **Construction Products Regulation**, which lays down harmonised rules for the marketing of construction products in the EU[173].
- The **non-binding EU Construction and Demolition Waste Protocol and Guidelines**, which aims at increasing confidence in the C&DW management process and the trust in the quality of C&D recycled materials, thereby fostering the development of C&DW management and recycling infrastructures in the EU[174].

These EU rules are supplemented by EU Standards, including:

- **EN-206 "Concrete – Specification, performance, production and conformity",** which specifies requirements (i.e., specification, performance, production, and conformity) for concrete used in construction;
- **EN-12620 "Aggregates for concrete",** which specifies the requirements (i.e., properties, production, and testing) for aggregates used in the production of concrete; and
- **EN-13242 "Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction",** which specifies the requirements (i.e., properties, production, and testing) for aggregates used in civil engineering and road construction projects.

At national and, in some cases, regional levels, EU Member States have established maximum allowable incorporation ratios for recycled aggregates in structural and non-structural concrete. These ratios vary based on the share of concrete in the composition of recycled aggregates[175] and the extent to which the waste concrete has been exposed to environmental conditions that can impact its durability[176].

Despite significant disparities among Member States, the maximum allowable incorporation ratios in structural concrete for recycled aggregates with a very high share of concrete and with little environmental exposure typically range between 20% and 50%. Notably, Denmark set itself apart as the country where the maximum allowable incorporation ratio in structural concrete is set at 100% for all type of coarse recycled aggregates with little environmental exposure. For recycled aggregates with a lower share of concrete or those exposed to more severe environmental conditions, the ratios applied by Member States are generally lower (i.e., between 5 and 20%), although significant disparities can also be noted.

Installing mandates

This study advocates that the regulatory framework of the concrete recycling sector could benefit from specific targeted amendments that would incentivize the increase of recycled aggregates in new building materials, supporting the circular economy, but also resulting in a direct increase of CDR. Moreover, and a step further, is to modify the regulatory framework to mandate a minimum amount of CDR when recycling concrete.

The EU could adopt EU-wide end-of-waste criteria for concrete that determines when concrete waste ceases to be classified as waste. This could include the requirements for the management systems that produce recycled concrete aggregates (RCA) and provide incentives for performing RCA carbonation. This will help to increase the acceptance of (carbonated) RCA by builders and, hence, strengthen the demand for them.

Within the Waste Framework Directive, the EU could also adopt a delegated act (pursuant to Article 27) to establish technical minimum standards for sorting and recycling activities related to concrete waste. Specifically, these technical minimum standards could mandate a minimum amount of carbonation when recycling concrete waste at recycling plants of sufficient size that are in close connection to CO_2 sources. Alternatively, these technical minimum standards could mandate a maximum amount of GHG emissions linked to the sorting and recycling activities related to concrete waste, towards which the carbonation of RCA could offset emissions produced from other activities.

Adapting standards

On standards, the national and regional standards could be adapted and harmonized to increase the maximum allowable incorporation ratios for (carbonated) recycled aggregates in structural and non-structural

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[171] European Commission (2008) Direct 08/98/EC.

[172] Note: The target has not been achieved, with only approximately 50% of such waste currently being recycled. There are notable disparities among Member States. Some countries, such as Denmark, the Netherlands, Estonia, and Germany, have established and implemented effective frameworks, achieving recycling rates between 85% and 98%. Conversely, other countries, including Greece, Italy, Malta, Portugal, and Sweden, have recycling rates for C&D waste that remain below 20%. For more information, see here and here.

[173] Official Journal of the European Union (2011) REGULATION (EU) No 305/2011

[174] European Commission (2016) EU construction & Demolition waste management protocol

[175] Note: "High quality RA - concrete waste", which composition is typically at least 90-95% made of concrete; "High quality RA", which composition is typically at least 80% made of concrete; and "Moderate quality RA", which composition is typically at least 70% made of concrete.

[176] Note: "Non-demanding", where the concrete is not exposed to aggressive conditions; "Low-demanding, where the concrete is exposed to conditions that can lead to carbonation, potentially reducing the pH and leading to corrosion of the steel reinforcement, and; "Demanding (all others)", where the concrete is exposed to severe conditions that can significantly impact its durability.

concrete, based on the latest scientific evidence, and considering the increased performance metrics when RCA are carbonated. Alternatively, the revised standards could be based on the key output parameters, such as compressive strength, tensile strength, shrinkage and creep, leaving open the amount of (carbonated) RCA that can be incorporated, as long as the environmental exposure is low.

As a step further, which would significantly enhance the use of (carbonated) RCA, the standards could mandate a minimum incorporation ratio of RCA (e.g., 25%) in all concrete mixes (i.e., structural and non-structural) and road construction products.

Using public procurement

Over 30% of cement in the EU is procured through public procurement practices[177], which highlights the significance of public procurement as a potential tool to scale up CDR practices in the concrete recycling sector. Since the additional cost of RCA carbonation in the total budgets of such public projects would be minimal, it presents a significant opportunity to drive CDR without any significant economic impacts. **If all public projects would mandate the use of carbonated RCA for their concrete projects, this alone would be sufficient to achieve the full potential of storing 2,6 Mt to 7,2 Mt of CO_2 each year in the EU.**

Governments on a national or local level could thus take advantage of this opportunity by mandating the use of carbonated RCA in concrete, to the levels allowed by the applicable standards, instead of natural aggregates in their public procurement schemes. This will help them to achieve their climate targets but will also boost the circular economy, create jobs and could position them as an innovation leader in this new technology area.

Mining waste management

Current policy landscape

Mining waste in Europe is currently managed under a broad regulatory framework, primarily governed by the EU Directive 2006/21/EC on the management of waste from extractive industries[178]. This regulation requires all operators of extractive activities to implement waste management plans reviewed every 5 years and aimed at preventing or reducing waste generation. Overall, it sets the detailed, more specific, and mandatory requirement for permit granting, financial guarantees, major accidents and waste facility closure. More broadly, this mining waste directive is complemented by the Waste Framework Directive (2025/1892) for which its most recent revision was adopted in 2025, establishing general waste principles such as the "polluter pay principle" or the "extended producer responsibility (EPR) principle"[179]. Nevertheless, while those directives aim to ensure the long-term stability of disposal facilities and prevent or minimize water and soil pollution arising from acid or alkaline, neither the Waste framework Directive nor the Extractive Waste Directive impose an explicit obligation to conduct CDR or to monitor GHG emissions.

In addition, those directives are complemented by the Industrial Emissions Directive (IED) and the Critical Raw Material Act (CRMA)[180]. The IED requires large industrial installations to operate under an integrated permit that covers their entire environmental performance. This directive uses the principles of the Best Available Techniques (BAT) in the reference document (MTWR BREF) in order to mitigate environmental impact of anthropogenic activities[181].

In the context of mining, this document (MTWR BREF) on the management of waste from extractive industries explicitly accounts and asks for the collection of data and monitoring of three different type of emissions: channelled emissions from mining operations, emissions from engines and diffuse emissions to air. In addition, it suggests the collection of information regarding the reduction of CO_2 emissions at the mining site as well as establishing site specific questionnaires. Nevertheless, information regarding decarbonisation in general remains very limited nor does it set any numerical binding emission limit values (ELVs) on GHG emissions.

Moreover, the CRMA is aimed at securing the sustainable supply of critical raw materials for the EU green transition, and while it actively encourages the recovery of critical raw materials from waste and sets targets on recycling, it does not directly target CDR or GHG reduction objectives.

Installing mandates

As a result of those highlighted limitations, it is proposed, in addition to recognising and accounting for CDR in GHG inventories, as mentioned before, the complementary revision of the Extractive Waste Directive to put a target on GHG emissions, for which the implementation of CDR technologies is acknowledged as means to reach the targets. Towards 2050, the target could be set as net negative, reflecting the high potential of this sector to become a net negative emitter due to the use of CDR technologies.

In addition, we propose the clear indication of enhanced mineralisation as a means of CDR, and hence decarbonization, in the BAT of the future revised MTWR BREF document under the IED .

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[177] Ramboll (2024) Green public procurement in construction
[178] European Commission (2016) REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS
[179] European Commission (2008) Waste Framework Directive
[180] European Commission (2024) European Critical Raw Materials Act
[181] EU (2018) Best Available Techniques (BAT) Reference Document for the Management of Waste from Extractive Industries

Conclusion

The three waste management sectors explored in this study (wastewater treatment, concrete recycling, and mine tailings management) demonstrate significant, technically validated carbon dioxide removal (CDR) potential at the pilot scale. If scaled globally, these sectors could collectively sequester between 254 and 356 Mt of CO_2 annually (with wastewater treatment plants capturing approximately 116 Mt/year, concrete recycling 7.6–18.9 Mt/year, and the mining waste management sector 131–221 Mt/year), all while imposing minimal economic impact on end-user costs (less than a 1–2% price increase). By deploying at large scale CDR technologies, these sectors could shift from being net-positive to net-negative emitters, thereby creating the necessary "carbon space" to offset emissions that are difficult to eliminate in their own sectors but also in other industries. This could thus be part of a broader net zero climate strategy.

Key opportunities to scaling CDR technologies in these sectors are both technological advancements that drive down costs, which can be stimulated by providing funding for research as well as for pilot and FOAK projects, but also regulatory instruments, such as improving national and corporate GHG accounting frameworks, installing policy mandates, CDR integration in public procurement and adapting product standards. An integrated policy framework is essential to enable the large-scale deployment of CDR projects within these sectors.

The policy mandates in the EU could be achieved by incorporation of GHG emission neutrality goals or separate CDR targets in each sector's main regulation, i.e. Urban Wastewater Treatment Directive, Waste Framework Directive, and Extractive Waste Directive. For concrete, integrating CDR requirements in the public procurement of concrete products would be an effective measure to scaling up CDR technologies in the sector. **These measures will have a very small impact on end-user prices in sectors that face low competition internationally (except mining) but have the potential of kickstarting the CDR industry in Europe, allowing the EU to become technology leaders, as well as reaching their net zero goal.**

About Carbon Gap

Carbon Gap is an independent, Brussels and UK-based non-profit organisation supporting Europe's unique opportunity to lead the responsible deployment of carbon dioxide removal (CDR) to fight climate change through independent and science-led advice.

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