Gemeente Amsterdam

NZKG noordzeekanaalgebied

Quick scan on the carbon removal potential in the Amsterdam Metropolitan Area and the North Sea Canal Area

Final Report

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south pole

BELLONA EUROPA

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About South Pole:

South Pole, recognised by the World Economic Forum as a Social Enterprise, has been at the forefront of decarbonisation since 2006. With its global climate solutions platform, South Pole develops and implements comprehensive strategies that turn climate action into long-term business opportunities for companies, governments and organisations around the world.

South Pole is also a leading project developer, and has provided nearly 1,000 projects in over 50 countries with climate finance to reduce over a gigaton of CO_2 emissions, and to provide social benefits to less privileged communities who are particularly vulnerable to climate change.

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About Bellona Europa:

Founded in 1994, Bellona Europa is an independent, non-profit organisation that meets environmental and climate challenges head-on. We are result-oriented and have a comprehensive and cross-sectoral approach to assess the economics, climate impacts and technical feasibility of necessary climate solutions. To do this, we work with civil society, academia, governments and polluting industries.

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List of acronyms and abbreviations

AMA	Amsterdam Metropolitan Area
BioCCS	Biomass with carbon capture and storage
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture, utilisation or storage
CDR	Carbon dioxide removal
CNI	Carbon Neutral Initiative
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CRCM	Carbon Removal Credit Mechanism
DAC	Direct air capture
DACS	Direct air capture and storage
ETS	Emissions Trading Scheme
EU	European Union
GJ	Gigajoule
Gt	Gigatonne
ha	Hectare
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram
kt	Kilotonne
kWh	Kilowatt-hour
LCA	Life cycle assessment
mm	millimetres
MRV	Monitoring, reporting and verification
Mt	Megatonne
NSCA	North Sea Canal Area
OCAP	Organic Carbon dioxide for Assimilation of Plants
PM	Particulate matter
SCS	Soil Carbon Storage
SDE++	Stimulation of sustainable energy production and climate transition
t	Tonne
TRL	Technology readiness level
UK	United Kingdom
WWTP	Wastewater treatment plant

Executive summary

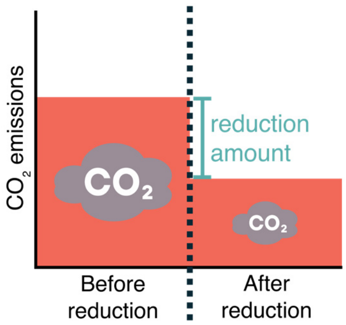
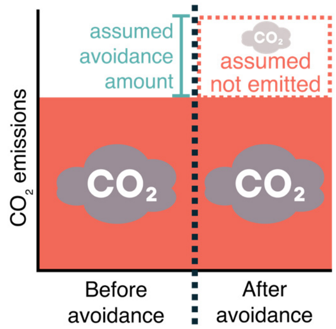
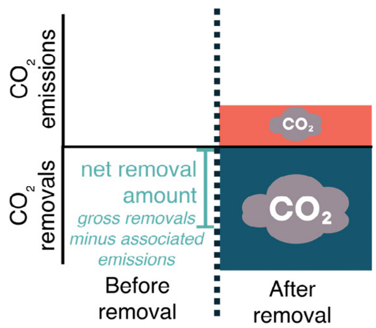
Introduction

Carbon dioxide removal (CDR) is the **physical**, **permanent**, and **net** removal of carbon dioxide (CO_2) from the atmosphere. CDR is an integral part of a net-zero transition – it is estimated that 1.9–16.1 $GtCO_2$ of removals will be required annually by 2050 to reach net zero. While CDR cannot replace emission reductions, it fulfils three crucial roles: i) reducing CO_2 emissions levels in the short-term; ii) neutralising residual emissions from hard-to-abate sectors in order to reach net zero CO_2 in the medium-term; and iii) achieving net negative CO_2 emissions in the long-term.

This report aims to map and assess the potential of CDR, as well as biogenic emission sources and storage opportunities in the Amsterdam Metropolitan Area and the North Sea Canal Area (NSCA). It also provides a set of high-level recommendations on what is needed to exploit such opportunities.

CDR technologies can be deployed at the urban scale, with the potential to capture emissions from industrial processes and municipal services. Each CDR solution presents its own benefits and limitations. For example, storage of CO_2 in geologic sinks (e.g. depleted oil and gas reservoirs, saline aquifers) requires investment in infrastructure and careful surveying and injection, but has a large capacity, is easily monitored and has a low risk of re-emission. Storage of CO_2 in biologic sinks (e.g. soils, biomass) is easier to implement and may have co-benefits (e.g. increased climate resilience of cities and agriculture), but has a higher risk of reversal (e.g. due to forest fires, disease, erosion), can be more difficult to effectively monitor, and the rate of carbon removal and the potential positive and negative co-effects are dependent on the exact environment and practices. Biomass with carbon capture and storage (bioCCS) is the storage of CO_2 from biogenic sources, which constitutes a CDR process. BioCCS comprises three necessary steps, from carbon source to carbon sink, namely the capture of biogenic CO_2 (e.g. from industrial processes), transport (e.g. via pipeline, truck, rail or ship) and permanent storage (e.g. in geological storage) of CO_2.

Different mitigation activities are not interchangeable

Reduction of emissions	Avoidance of emissions	Removal of CO_2
occurs when: a change in a greenhouse gas emitting activity results in that activity emitting less greenhouse gases than it did before or in a reduction of the activity which emits greenhouse gases.	**occurs when:** an activity is assumed to result in less CO_2 being emitted compared to an alternative scenario, usually 'business-as-usual'.	**occurs when:** greenhouse gases are physically and permanently removed from the atmosphere. (If the extracted atmospheric CO_2 is re-released into the atmosphere, it is not a removal, but rather a delayed emission).
		
has the net effect that: the amount of CO_2 in the atmosphere increases (as CO_2 is still emitted), but less quickly than it did before.	**has the net effect that:** the amount of CO_2 in the atmosphere is assumed to increase less than if the avoidance had not occurred. The net effect of emission avoidance is inherently unverifiable.	**has the net effect of:** The amount of physical CO_2 in the atmosphere decreases.

Source: Bellona (2022)

Assessment: BioCCS

Interviews were conducted with relevant companies along the bioCCS chain. These include: i) biogenic CO_2 emitters, such as from the combustion on biogenic waste, biofuel production and wastewater treatment; ii) CO_2 transport providers, namely by pipeline; and iii) CO_2 storage providers, through geological storage or carbon mineralisation in durable products. The below tables provide an overview of the expected scale of biogenic CO_2 to be emitted, transported and stored with these various options. It also includes an indicative view of the potential of each option to generate CDR in the Amsterdam Metropolitan Area and the NSCA, by 2030 and by 2050.

Overview of sources

Type of source	Description	(Expected) scale of biogenic CO_2 supply for CDR	Potential to store biogenic CO_2 for CDR purposes by 2030	Potential to store biogenic CO_2 for CDR purposes by 2050
Combustion of biogenic waste	Combustion of waste for steam, heat and electricity. While ~60% of AEB's carbon emissions are biogenic, it is the largest source of biogenic CO_2 identified in the region. Planned CO_2 capture unit.	**~450,000 t CO_2/ year (expected to grow)**	**Promising** Existing plans for carbon capture and storage (CCS) through the Aramis project could become operational by 2028–2029.	**Very promising** Geological storage could account for a greater part of the captured biogenic CO_2, as the business model is proved to be viable.
Biofuel production	Production of biogas, biomethane or biomethanol through fermentation of biomass. Biogenic CO_2 streams are separated and so can be captured. Advanced Methanol Amsterdam currently sending to greenhouses rather than for storage.	**Unclear** – use vs storage	**Less promising** Operation will only start in late 2025, with initial biogenic CO_2 streams going to greenhouses.	**Promising** Volumes of biogenic CO_2 are expected to increase, with increase of hydrogen production and the possibility of geological storage as more CCS projects come online.
Wastewater treatment	Waternet is the largest wastewater treatment plant in the Amsterdam harbour area. There are currently no plans to capture and store CO_2 before 2030, but they are piloting green gas installations.	**Unclear**	**Not promising at present** There are currently no plans to capture CO_2 before 2030.	**Less promising** Capturing biogenic CO_2 would require process changes, as streams are currently considered too small and too diluted to capture.

Overview of transport options

Type of transport	Description	(Expected) scale of CO_2 transport	Potential to store biogenic CO_2 for CDR purposes by 2030	Potential to store biogenic CO_2 for CDR purposes by 2050
Pipelines	Transport from CO_2 sources to permanent storage. Options include trucks, rail and ships for liquified CO_2 and pipelines for gaseous CO_2. OCAP is a transporter and supplier of CO_2, especially to greenhouses in the south of the NL, via its own pipeline. Delivery for other applications often proves to be difficult, given the small purchase volumes and the high quality CO_2 that is required.	**Transports 600,000 t CO_2/year, expected to reach 2,000,000 t CO_2/ year** **Unclear how much for storage vs use**	**Promising** OCAP is the only existing pipeline network connecting Amsterdam to the CO_2 storage infrastructure in the Port of Rotterdam. As such, it is a central element of the CDR supply chain in the short-term. It is already connected to sources of biogenic CO_2, but currently for use rather than storage. Smaller volumes of biogenic carbon could be rerouted to permanent storage.	**Very promising** With developing and expanding legislation and regulation on CDR, it can be expected that OCAP will expand its capacity to accommodate a larger share of its CO_2 to geological storage projects in the Port of Rotterdam.

Overview of sinks

Type of source	Description	(Expected) scale of biogenic CO_2 supply for CDR	Potential to store biogenic CO_2 for CDR purposes by 2030	Potential to store biogenic CO_2 for CDR purposes by 2050
Geological storage	CO_2 from industry is transported by pipeline to platforms in the North Sea, from which it is pumped into empty gas fields beneath the North Sea..	Unclear – expected in **millions of tonnes of CO_2**	**Promising** Porthos operational but sold out. Aramis should be operational and likely include biogenic carbon	**Very promising** Millions of tonnes of CO_2 per year will be stored in the North Sea, likely with additional projects coming online.
Carbon mineralisation	Various carbon mineralisation technologies, including: carbonates and aggregates from waste; ready-mix concrete from CO_2; and pre-cast concrete from CO_2. Not currently in operation in the Netherlands, but this technology is proven and can be rapidly implemented.	Unclear – expected in **thousands of tonnes of CO_2**	**Less promising** Carbon mineralisation in building products can be implemented relatively quickly, if the biogenic CO_2 inputs can be sourced. However, the scale of CDR achieved is likely to be small	**Promising** It is expected there will be more readily available sources of biogenic CO_2, though likely that only limited volumes would be used for mineralisation in building products in the project area.

BioCCS barriers

From the interviews conducted, the following barriers were identified as hindering the development and deployment of bioCCS.

- **Regulatory:** lengthy processes for permitting and end-of-waste status
- **Policy:** absence of CDR-specific targets and legislation
- **Financial:** insufficient incentives to deploy bioCCS at scale
- **Infrastructure:** lack of accessible transport networks and long lead time
- **Public perception:** public awareness and acceptance, e.g. on mitigation deterrence; sustainability credentials of biomass

BioCCS enabling factors

From the interviews conducted, the following enabling factors were identified as possible solutions or incentives to the above barriers to bioCCS.

- **Legislative and regulatory:** streamlined permitting process; CDR-specific policy and targets for clear role and use
- **Financial:** infrastructure development; higher subsidies; valuation of CO_2
- **Others:** stronger political support; pilot projects support; transparency

Assessment: Standalone CDR

Similarly to bioCCS, interviews were conducted with companies involved in standalone CDR solutions, which combine the capture, transport and storage of CO_2, namely: i) direct air capture and storage; ii) enhanced weathering; iii) biochar; iv) soil carbon storage; and v) afforestation. The table below provides an overview of findings and indicative potential of these options to generate CDR by 2030 and 2050, specifically in the Amsterdam Metropolitan Area and NSCA.

Overview of standalone CDR solutions

CDR option	Description	Potential of CDR by 2030	Potential (scale) of CDR by 2050	Key determinants of potential
Direct air capture and storage (DACS)	Chemical extraction of CO_2 from the atmosphere paired with geologic storage.	**Not promising** Very energy intensive	**Promising** **1+ Mt** per year but entirely dependent on competition for resources.	• Rate of technological learning • Availability of low-carbon energy • Access to geologic storage
Enhanced weathering	Spreading of ground minerals that dissolve atmospheric CO_2 into soil.	**Not promising** Uptake takes years to decades; Environmental uncertainties	**Less promising** Ca. **1 Mt** cumulative in Amsterdam municipality	• Size of ground mineral → speed of CO_2 uptake • Availability of land for spreading • Legal status
Biochar	Stable form of charcoal that is then added to soil or buried.	**Less promising** Scalable but many remaining uncertainties	**Less promising** If used in soils, ca. **1–3 Mt cumulative** removal in greater Amsterdam region	• Availability of sustainable biomass • Development of robust monitoring and verification • Legal status
Soil carbon storage	Land management practices to increase organic carbon in soils.	**Not promising** Management must be tailored to regional soils	**Less promising** Ca. **35 kt** per year in greater Amsterdam region	• Uptake by farmers • Quality of continuous management • Development of reliable and low-cost monitoring and verification
Afforestation	Cultivation of dedicated long-rotation biomass.	**Less promising** Uptake takes years to decades; Typically popular	**Less promising** **10's–100's kt** per year in greater Amsterdam region	• Availability of land for planting • Quality of continuous management

Standalone CDR barriers

The interviews conducted highlighted the following barriers to the development and deployment of standalone CDR solutions.

- **Regional uncertainties:** impacts of land-based CDR are location-specific
- **Competition for resources:** including land, energy, and biomass
- **Regulatory ambiguity:** including land use and 'foreign substance' restrictions
- **Lack of financial incentive:** neither carbon storage nor 'ecosystem services' are currently valued

Standalone CDR enabling factors

Similarly, the following enabling factors were identified as possible solutions or incentives to the above barriers to standalone CDR solutions.

- **Siting flexibility:** not limited to industrial areas or (except DACS) access to geologic storage
- **Potential co-benefits:** such as reduced heat island effect, urban greening, improved crop yields, soil water retention, etc
- **Support for pilots:** to assess region-specific scaling and MRV potentials

Conclusion

Key takeaways

→ **There is no net zero without CDR** – CDR should be an integral part of a municipal and regional climate strategy. However, this should not come at the expense of deep emission reductions.

→ Individual CDR solutions each have their **own merits and limitations**, and should not be considered equivalent.

→ **While there is potential for CDR in Amsterdam and the NCSA, the development and deployment of these processes are hindered by a number of factors**, as addressed in this report.

Key recommendations

→ **Set a CDR-specific target and roadmap.**

- Including volumes per year and timeline, to enable focused approach
- Identifying CDR mix that enables target achievement
- This enables the development of solutions conducive to target, including financial support

→ **Dedicate more resources to research for, development and accounting of CDR.**

- Conducting more comprehensive studies for quantitative CDR potential
- Developing reporting requirements for biogenic emissions
- Evaluating sustainability of biomass use

→ **Take a more active role in supporting CDR activities at the municipal and regional scales.**

- Streamlining regulation processes
- Supporting pilot projects for proof-of-concept
- Designing funding pathways for CDR
- Raising awareness for social legitimacy and commercial interest
- Promote CDR activities at the national level, incl. through lobbying national government

Call to action

Cities are a critical arena for climate action. Urban areas will account for over half of global increase in carbon emissions by 2030. They concentrate economic, political and cultural activity, and are motors of change and innovation, able to transform human structures, and design, facilitate and implement concrete actions. Cities are a critical actor in the multi-level governance of climate politics, at times acting independently from their national government. The city is therefore an important scale for climate and removals action, particularly when considering the ubiquitous and inclusive approaches needed to deploy CDR. Although a large number of cities have committed to net zero, they may not have the knowledge, capacity or network to integrate removals in their strategies or implement city-scale removal solutions. It is crucial that the municipality of Amsterdam and the NSCA deepen their knowledge, build their capacity and expand their network to reach their climate goals.

The municipality of Amsterdam is already at the forefront of climate change action, having committed to ambitious climate goals and taking part in initiatives such as the EU Mission for Climate-Neutral and Smart Cities. It is also taking steps to develop its understanding of the potential for emissions reductions and removals, through this study and a similar quick scan conducted on CCU potential. Its proximity to biogenic emission sources in surrounding industrial areas and potentially massive storage potential in the North Sea makes it a prime candidate to explore CDR at a large scale. By being an early adopter and promoter of CDR, the region also stands to become a hub for CDR solutions and industry, attracting businesses and stimulating a sector increasingly recognised as essential to mitigating climate change.

The municipality of Amsterdam and NSCA should contribute to driving the acceleration toward the deployment of CDR, thereby catalysing private sector action, rather than the opposite. CDR, as essential to reach climate goals, must be considered a public good, rather than a purely commercial or industrial undertaking. In the same way that local governments provide waste management services (e.g. for sewage and water), the provision of – or promotion of – CO_2 management services could be foreseen to be an essential public service.

Next steps for the Amsterdam Metropolitan Area and North Sea Canal Area

- → **Address the end-of-waste regulation**, which must be streamlined to facilitate the capture of both biogenic and non-biogenic CO_2.
- → **Comprehensively identify and quantify the opportunities** for the capture, transport and storage of biogenic emissions, and for the use of standalone CDR solutions.
- → **Explicitly address the role of CDR** envisaged in municipal and regional climate strategies.
- → **Set a CDR-specific target** to catalyse investment in and development of CDR activities.
- → **Take an active role in innovation**, e.g. by showcasing demonstrations and pilots.
- → **Convene a multi-stakeholder group** to inform a CDR deployment roadmap.
- → **Advocate with other Dutch and international cities** for national CDR policies and funding.
- → **Convene a citizen assembly on removals** to start building social legitimacy.

1. Introduction

The ongoing climate crisis requires the rapid reduction of greenhouse gas emissions, at all scales and sectors, to near-zero in the coming decades. This transition requires aligning efforts not only by nations and citizens, but also industries and municipalities. So as the global commitment to 'net zero' implied by the ambitions of the Paris Agreement is reflected in the national climate policy of the Netherlands, so too is it reflected in the ambitions of regions such as the Amsterdam Metropolitan Area and the North Sea Canal Area (NSCA).

A large number of cities have committed to net zero, but may not have the knowledge, capacity or network to integrate removals (an integral part of the net-zero transition) in their strategies or implement city-scale removal solutions. The Amsterdam municipality has stated in its Climate Neutral Roadmap the objective to reduce carbon emissions by 55% in 2030 and 95% in 2050, compared to 1990 levels. The more recent Coalition Agreement 2022–2026 has set the more ambitious goal of reducing CO_2 emissions by 60% in 2030. Currently foreseen interventions, however, would be insufficient to meet these objectives.

Against this background, this 'quick scan' focuses on one aspect of the transition to a net-zero society, namely the role of carbon dioxide removal (CDR), which is needed to supplement emission reduction efforts and, in the long term, to balance out any residual emissions of greenhouse gases. It intends to assess the carbon removal potential in the wider cosmopolitan area, including the industrial area in the Zaanstreek. **A national quick scan on negative emissions was conducted**, which found additional progress must be made on: i) central government policy development aimed at negative emissions; ii) research focused on the CDR value chain; and iii) research aimed at developing and implementing CDR-related policy. It recommended that similar scans are conducted along carbon value chains at a regional level.

This report represents the first efforts at positioning CDR in the overall municipal and regional climate policy. It will provide a basis for the development of an integral vision on the role of carbon removal in the city's long-term climate strategy and associated municipal policies. The goal of this report is to assess potential CDR options based on currently available regional data, as well as key drivers and barriers to CDR implementation, and to recommend initial actions for both evaluation and implementation of promising CDR options.

This report is divided into five parts:

Context, which first defines CDR and presents a summary of the wider policy context surrounding Amsterdam's role in the net-zero transition.

Preconditions for CDR, which provides a more in-depth explanation of how CDR can be achieved. This is followed by an explanation of the necessary preconditions for achieving CDR.

Quick scan: BioCCS, which focuses on the potential for focus on 'biomass with carbon capture and storage' options for the industry in the NCSA, and local drivers and barriers, informed primarily by interviews with relevant stakeholders.

Quick scan: Standalone CDR, where other CDR options are also described and discussed, including direct air capture and storage, enhanced weathering, biochar, soil carbon storage, and afforestation.

Conclusion and recommendations, which concludes the report with a series of recommendations for future research and policies on CDR in the Amsterdam region.

2. Context

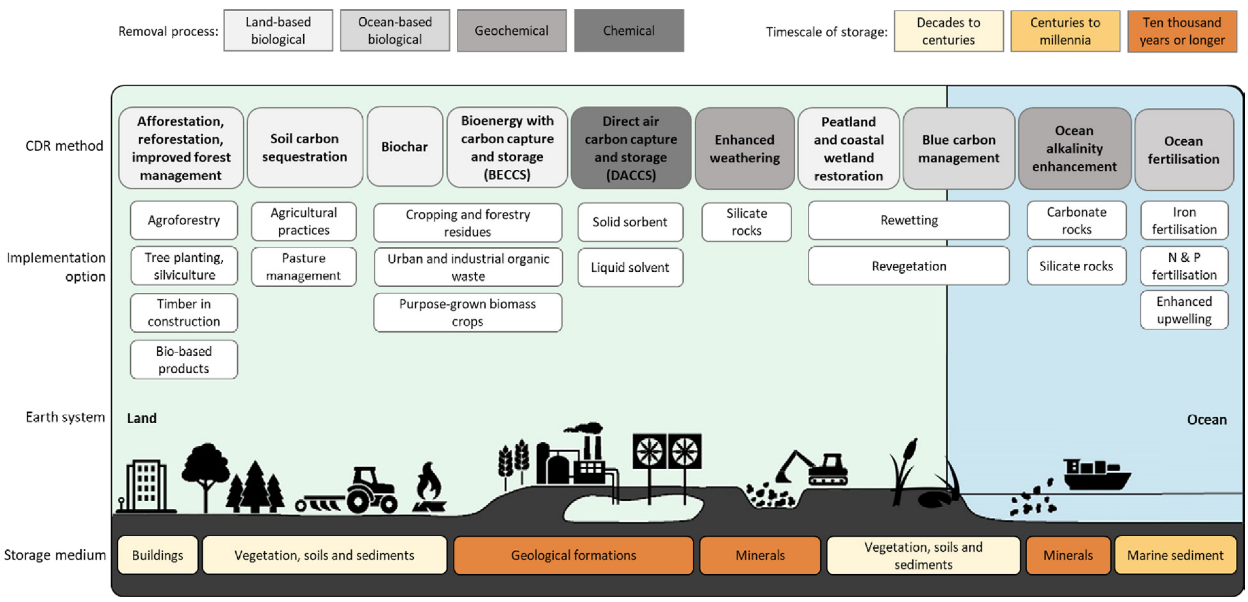
2.1 What is CDR?

Carbon dioxide removal (CDR) is the extraction of carbon dioxide (CO_2) from the atmosphere with the specific purpose of reducing atmospheric greenhouse gas concentrations, thereby leading to the reduction in global warming. The variety of CDR methods are presented in Figure 1.

To qualify, a CDR activity must satisfy four minimum criteria, summarised by [Tanzer and Ramirez (2019)]:

1. Physical greenhouse gases are removed from the atmosphere.
2. The removed gases are stored out of the atmosphere in a manner intended to be permanent.
3. Upstream and downstream greenhouse gas emissions associated with the removal and storage process, such as biomass origin, energy use, gas fate, and co-product fate, are comprehensively estimated and included in the emission balance.
4. The total quantity of atmospheric greenhouse gases removed and permanently stored is greater than the total quantity of greenhouse gases emitted to the atmosphere.

Figure 1: CDR is the physical, permanent, and net removal of greenhouse gases from the atmosphere. Once emitted, CO_2 may remain in the atmosphere for hundreds of years. A variety of options to remove and store atmospheric are available, but ensuring that these activities result in true CDR requires managing storage to prevent or compensate for any potential re-emissions, and to ensure that the quantification of CDR accounts for the greenhouse gas emissions in the removal and storage processes and their supply chains.



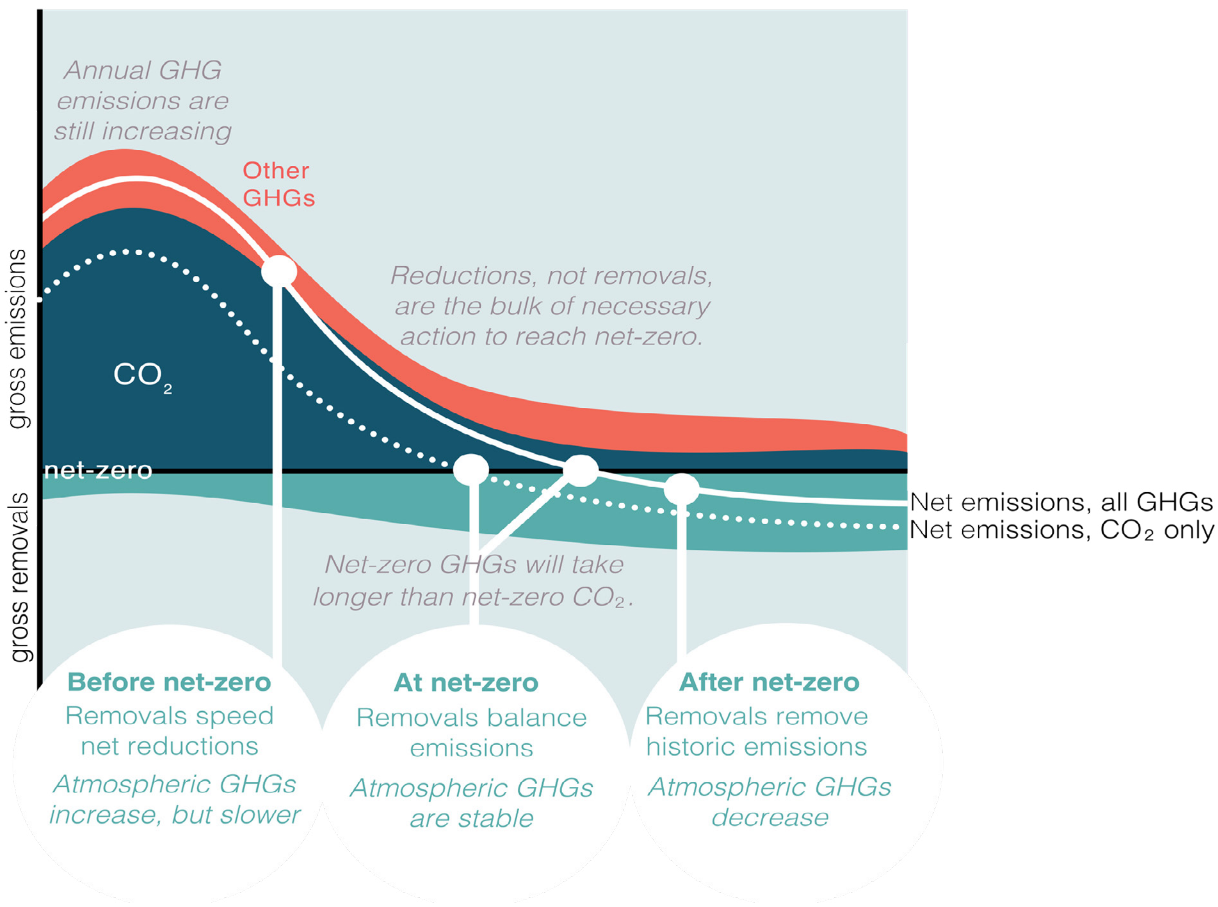
Source: IPCC AR6 WGIII, Chapter 12 (Box 8, Figure 1)

The latest IPCC report sees **CDR as a necessary part of limiting global warming**, with three sequential roles, as follows (Figure 2).

1. **Net reduction** of greenhouse gas emissions: As a supplement to rapid massive-scale reductions to get to net zero faster
2. **Net zero**: Then, to maintain net zero by compensating for residual emissions
3. **Net negative**: Finally, to remove historical emissions

This implies that there can be no net zero or net negative emissions without the use of CDR.

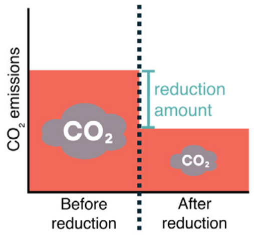
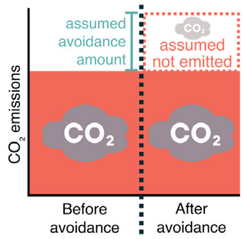
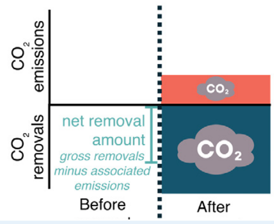
Figure 2: The sequential roles of carbon dioxide removal over time



Source: Bellona (2022), adapted from: IPCC AR6 WGIII, Chapter 12 (Box 8, FIgure 2)

While CDR is the only activity that can physically extract CO_2 from the atmosphere, an effective climate policy portfolio minimises the need for resource-intensive CDR by reducing existing greenhouse gas emissions and avoiding new additional greenhouse gas emissions. **Reduction, avoidance and removals are all necessary forms of climate mitigation but are not interchangeable** (Table 1). Avoiding new emissions does not slow how fast existing emissions enter the atmosphere and reducing existing emissions does not remove already-emitted CO_2 from the atmosphere.

Table 1: Different mitigation activities are not interchangeable

<table>
<tr><th>Reduction of emissions</th><th>Avoidance of emissions</th><th>Removal of CO_2</th></tr>
<tr><td>occurs when: a change in a greenhouse gas emitting activity results in that activity emitting less greenhouse gases than it did before or in a reduction of the activity which emits greenhouse gases.
</td><td>occurs when: an activity is assumed to result in less CO_2 being emitted compared to an alternative scenario, usually ‘business-as-usual’.
</td><td>occurs when: greenhouse gases are physically and permanently removed from the atmosphere.
(If the extracted atmospheric CO_2 is re-released into the atmosphere, it is not a removal, but rather a delayed emission).
</td></tr>
<tr><td>is measured in: kg CO_2eq not emitted, compared to a measured historical baseline .</td><td>is measured in: kg CO_2eq that are assumed would have been emitted otherwise (estimated emission avoidance is wholly dependent on the selected counterfactual).</td><td>is measured in: net kg CO_2eq removed from the atmosphere (kg removed minus kg emitted in the removal and storage process and supply chains).</td></tr>
<tr><td>has the net effect that: the amount of CO_2 in the atmosphere increases (as CO_2 is still emitted), but less quickly than it did before.</td><td>has the net effect that: the amount of CO_2 in the atmosphere is assumed to increase less than if the avoidance had not occurred. The net effect of emission avoidance is inherently unverifiable.</td><td>has the net effect of: The amount of physical CO_2 in the atmosphere decreases.</td></tr>
</table>

Source: Bellona (2022)

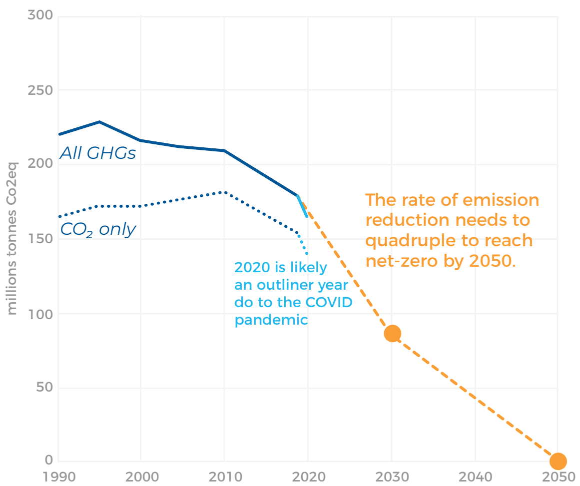
2.2 National and local policy context

The Netherlands has set targets to reduce its emissions by 49% (compared to 1990) by 2030 and 95% by 2050 (Figure 3). Numerous solutions are needed to achieve the goals, such as the transition to sustainable energy sources, energy savings, reuse of materials and the capture, transport and geologic storage of CO_2 (Carbon Capture and Storage [CCS]). CCS in particular is a fundamental component of both mitigating industrial fossil emissions and for the capture and storage of atmospheric CO_2.

The Netherlands is ideally suited for CCS, namely because:

- The energy-intensive industry with large CO_2 emissions is concentrated in a few places;
- Those clusters are close to the coast, which is favourable for offshore storage;
- The Netherlands has considerable storage capacity under the North Sea in the form of empty oil and gas fields;
- The oil and gas infrastructure is ideal for reuse for transport and storage of CO_2; and
- The Netherlands has excellent logistical advantages for CO_2 transport.

Figure 3: Netherlands greenhouse gas emissions – historical reality and future ambitions



Currently, there is a strategy on CCS in the Netherlands but not yet on CDR. There are large CCS projects that are part of the Climate Agreement such as Porthos, Aramis and the now-suspended Athos. The Netherlands could further play a pioneering role in deploying CDR and CCS, given the favourable starting position in the field of storage, knowledge and companies.

National instruments that are relevant to CDR and CCS include the following.

- **Climate Agreement:** part of the Dutch climate policy, setting out long-term targets to reduce emissions by 55% by 2030 and to net-zero by 2050. It lays out emission reduction commitments in five specific sectors (built environment; mobility; industry; agriculture and land use; electricity) as well as cross-sectoral sectors, including biomass and market financing. Such commitments include the provision of subsidies, development of standards and increased taxation of emissions. It does not explicitly mention CDR but includes provisions for CCS and CCU, and alludes to the concept of negative emissions.
- **Stimulation of sustainable energy production and climate transition (SDE++):** subsidy for companies and organisations in sectors such as industry, mobility, agriculture and the built environment. Subsidised processes include biomass combustion, biomass gasification and fermentation, CCS and carbon capture and utilisation (CCU). The subsidy horizon for fossil-based CCS is capped at 2035, but this should not apply to carbon removal solutions – these are currently not explicitly eligible under the subsidy instrument.
- **Topsector Energy, Multi-annual Mission-driven Innovation Programme (MMIP) 6 'Closing Industrial Chain':** This MMIP is an innovation agenda which focuses on CCS and a range of CCU applications, including in combination with BECCS and DAC, as well as the development of biochar.
- **Demonstration of Energy and Climate Innovation scheme (DEI+):** subsidy scheme focused on pilot and demonstration projects, with CCUS as one of the themes. CCUS is also mentioned in the context of realising negative emissions in the long term.
- **National CO_2 tax:** carbon levy announced in the Climate Agreement. It applies to fossil CO_2 emissions already under the EU ETS, but also to waste incineration plants which are currently outside the ETS.

The Municipality of Amsterdam is situated in the North Sea Canal Area (NSCA), which includes the industrial centres of Ijmond and the Amsterdam Port. In 2018, the North Sea Canal Area emitted 18.3 $MtCO_2$ (representing ~13% of national CO_2 emissions) of which 12.6 Mt are associated with steel production at Tata Steel in Ijmuiden (both direct and indirect emissions).

Reflecting the wider ambitions of the Netherlands and the EU, the NSCA also intends to be climate neutral by 2050, including reducing emissions by nearly half in 2030. This is an undertaking of a grand scale, and is envisioned by the 'Cluster Energy Strategy 1.0' to involve a tripling of electricity demand and a halving of gas demand by 2030. Additionally, CCS is anticipated to play a large role in the decarbonization potential of the region, to be 1.8 Mt captured and stored in 2025, up to 5–8 million tonnes in 2030.

EU policy context

The EU aims to reach climate neutrality by 2050, primarily by preventing greenhouse gas emissions, of which CO_2 is the most significant. However, not all CO_2 emissions can be easily prevented, particularly in the near term. In addition to CO_2 emissions from combusting carbon-based fuels, carbon is also a raw material for industry and is used to make medicines, chemicals, plastics and food. The EU recognises this continued need for carbon in the 'Sustainable Carbon Cycles' communication of December 2021. Since then, a rethink of carbon cycles has been high on the agenda, with the first action point being to reduce reliance on carbon, the second to recycle carbon from waste streams and biomass and the third to scale up solutions that remove CO_2 from the atmosphere. The basis of this are two pillars, namely: 'Carbon Farming' and 'Industrial CCUS'. The first focuses on the role of land to capture and store carbon and the second on the role of industry to shift towards sustainable (biogenic and atmospheric) CO_2 and the development of geological storage.

In order to highlight the role of 'Industrial CCUS' to help achieve the EU's climate neutrality target, it has drawn up the following 'Industrial Sustainable Carbon Challenge':

- By 2028, every tonne of CO_2 captured, transported, used and stored by industry must be reported and its origin (biogenic, fossil, atmospheric) recorded.
- At least 20% of the carbon used in chemical or plastic products must be of biogenic or atmospheric origin by 2030.
- By 2030, 5 $MtCO_2$ per year must be removed from the atmosphere and permanently stored.

The EU already recognises the significance of bioCCS. The EU Energy Roadmap 2050 states that 'for all fossil fuels, Carbon Capture and Storage will have to be applied from around 2030 onwards in the power sector in order to reach decarbonisation targets', as well as '[CCS] combined with biomass could deliver 'carbon negative' values.'

The main European instruments that influence CDR and CCS projects are:

Renewable Energy Directive:
The RED establishes targets and general criteria for Member States to subsidise the deployment of renewable energy, including the types of biomass feedstocks which can be used for bioenergy.

CO_2 Storage Directive
This directive establishes a legal framework to regulate the storage of CO_2 in geological formations. The Commission is planning to update the guidance documents, which should facilitate the transposition of the directive into national law.

EU ETS
The EU Emission Trading System is a cap-and-trade system and is the foremost climate instrument in the bloc. In establishing a price and a limit for polluting, the system encourages polluters to handle their emissions, or to pay someone else in the system who can handle their emissions more cost-effectively. The ETS only covers fossil emissions.

Innovation Fund
This fund is financed by some of the revenues generated by the EU ETS, approximately €10 billion (depending on the price of CO_2 allowances). This money is spent on innovative projects which can substantially reduce emissions and bring a particular process to market scale. A handful of full chain CO_2 capture and storage projects received funding in the latest round. Previous rounds supported the Stockholm Exergi BioCCS project.

Horizon Europe
The EU's eminent research programme has dedicated streams for the decarbonisation of industry, targeting industrial clusters which could benefit from CO_2 transport and storage infrastructure.

Carbon Removal Certification Mechanism (CRCM):
This mechanism is effectively a carbon accounting mechanism which will be used to quantify and verify the quantity of carbon that is stored and how long that carbon is stored. The eventual outcome is expected to be a certificate that can demonstrably prove that CO_2 is being removed from the atmosphere and permanently stored. Criteria are currently being drawn up for the definition of 'removal', the duration of the CO_2 storage, the potential for reversals, application of the certificates, etc. These criteria will determine which solutions are in the scope of the mechanism, but will not yet determine how and where these certificates will be used.

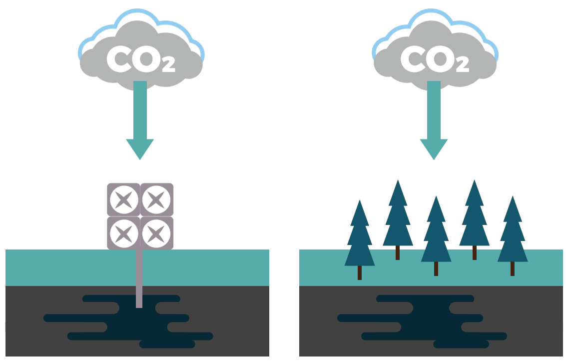
3. Preconditions for carbon dioxide removal

From a physical perspective, effective carbon dioxide removal (CDR) must entail **physical removal** of CO_2 from the atmosphere; **permanent storage** of the removed CO_2 (ideally for hundreds of years or more), and must **not emit more than is removed**.

3.1 Ensuring physical removals

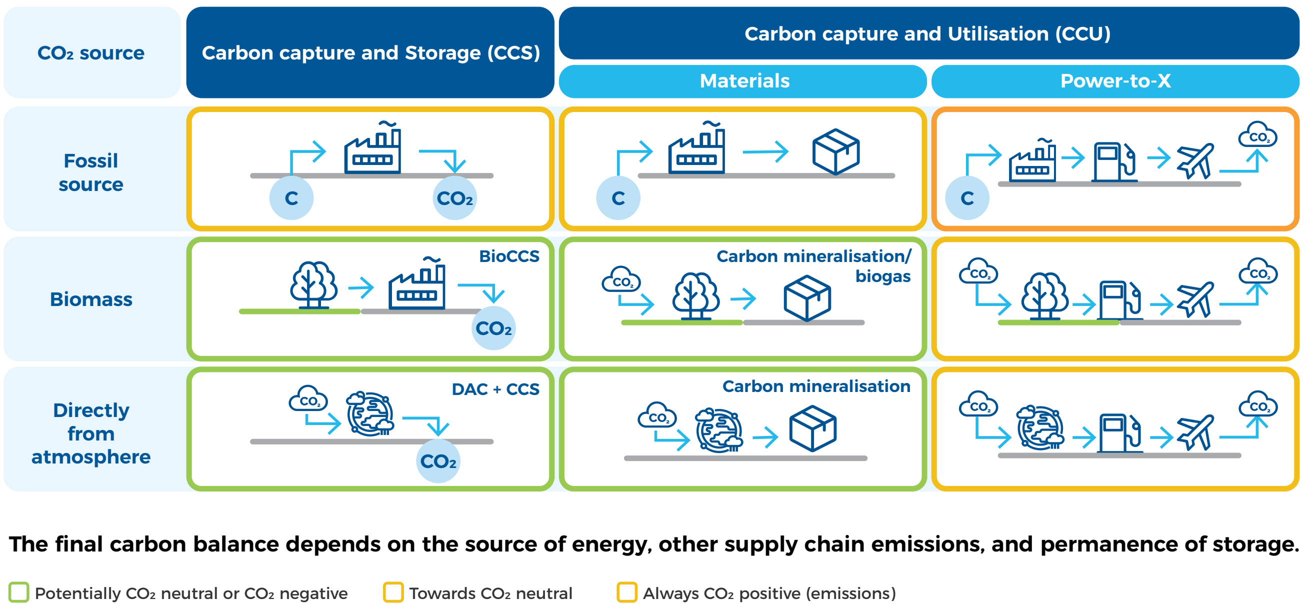
CDR requires that CO_2 is physically extracted from the atmosphere (Figure 4). CO_2 can be extracted from the atmosphere via natural processes, including **photosynthesis** of biomass and the **weathering** and **carbonation** of certain types of minerals, as well as by artificial processes, such as **chemical absorption** via a solvent or solid sorbent. **If a system involves only fossil carbon (e.g. natural gas, oil, limestone, coal), it cannot result in CDR, even if combined with carbon capture and storage (Figure 5)**. Preventing the release of fossil emissions, such as via CCS, is a vital component of climate change mitigation, but is a *reduction* activity, not a *removal* (see Table 1).

Figure 4: CDR requires physical extraction of atmospheric carbon.



A CDR system requires that CO_2 is physically extracted from the atmosphere, such as via photosynthesis of biomass or direct air capture with chemicals. If a system only contains fossil carbon, it cannot result in CDR.

Figure 5: Only systems that pair physical atmospheric removals with permanent storage can potentially be CO_2 negative.



Source: ClimateWorks Foundation

Removals happen at different speeds. Natural weathering and carbonation processes operate on the scale of decades to millennia, though they can be accelerated by human intervention. Photosynthesis of biomass occurs on a scale of months to decades, depending on the life cycle of the biomass. Chemical absorption operates on a timescale of minutes to days. Speed comes with a cost: generally, the faster the CO_2 is removed from the atmosphere, the more energy the removal process requires.

Some mechanisms of removals

CO_2 can be removed from the atmosphere by a variety of processes that capture the diluted CO_2 into a material or chemical. Note that these processes can also be used to capture non-atmospheric CO_2 (e.g. fossil flue gases) but only count as removals if they are used to capture atmospheric CO_2.

Photosynthesis is the process by which plants uses energy from sunlight to convert CO_2 from the atmosphere and water from the soil into sugars and oxygen. The sugars are then used for growth, storing the carbon in the plant, while the oxygen is released into the atmosphere. The speed of photosynthesis is dependent both on the type of biomass and environmental conditions.

Weathering is the process by which certain rocks interact with water and atmospheric CO_2, dissolving the rock with CO_2 bound in it. The dissolved rock sinks into the soil and, eventually, to underground aquifers or the oceans. Natural weathering occurs over decades to millennia, and can be sped up by increasing the surface area exposed to air.

Mineralization is an adsorption process, by which CO_2 binds to the surface of certain materials, such as lime (CaO) and magnesium oxide (MgO). The CO_2 could then either be left in the material itself, or the material could be heated, releasing the CO_2 gas to be transported and stored elsewhere, and the material can then be reused. The speed of mineralization depends on the available surface area of the material, slowing down considerably when needing to permeate below the mineral's surface.

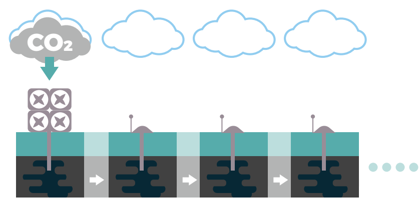
Absorption is a process by which CO_2 is captured into a chemical, such as a liquid solvent. The CO_2 is then released from the absorbent in a concentrated stream that can be more easily transported and stored, and the absorbent can be reused. Many modern CO_2 capture units use amine-based solvents to absorb CO_2.

3.2 Ensuring permanent storage

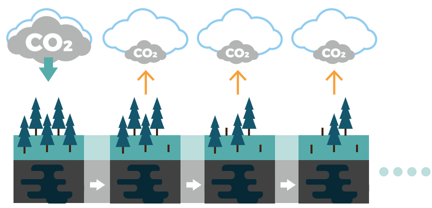
Once removed, the CO_2 must be kept out of the atmosphere permanently. When CO_2 is emitted to the atmosphere, it remains there for 300–1000 years. Therefore, if at any point in that timeframe, the CO_2 is re-emitted to the atmosphere, it is not a removal, but rather a delayed emission. In particular, **if the CO_2 is reused in short-lived products such as fuel, fertiliser, paper, or plastics, this will result in re-emission and is not CDR**.

Even for long-term storage options, the potential for re-emission, or **'risk of reversal'**, **is one of the key concerns of any CDR activity**. Different storage media have different risks of reversals that must be managed (Figure 6). **Storage in geologic reservoirs is effectively permanent**, with negligible risk of reversal after injection has stopped. Still, the geologic storage site must be carefully chosen, prepared, and monitored to prevent the risk of leakage. Storage in standing biomass (e.g. forests) has a higher risk of reversal due to the possibility of fire, disease, drought, and mismanagement. **Storage in higher-risk sinks, such as biomass and soils requires planning – and financing – for ongoing maintenance and mitigating potential reversal, in perpetuity**. The cost of CDR is not only the price of extracting CO_2 from the atmosphere, but also the cost of maintaining the removal.

Figure 6: Geologic and biologic sinks are fundamentally different.



Storage of CO_2 in geologic sinks requires investment in robust surveying, infrastructure, and controlled injection. Geologic storage is effectively permanent, with a near-zero risk of reversal after the site has been closed.



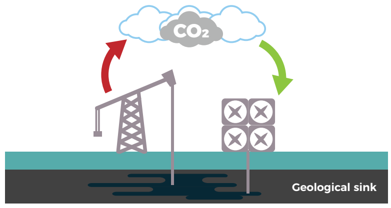
Storage of CO_2 in biologic sinks, such as forests or soils, has a high risk of reversal and requires continuous management to prevent and replace any losses due to drought, fire, disease, pests, or human activity.

Source: Bellona Foundation (2022)

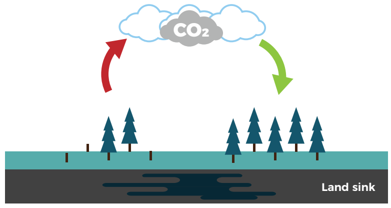
Another key issue is the **monitorability of storage.** CO_2 stored in static, concentrated reservoirs, such as geologic formations or forests have existing methodologies and tools to physically verify the amount of carbon stored. CO_2 stored in products, with the potential exception of buildings and other static infrastructure, is unlikely to be effectively monitorable, due to the dispersed nature of the storage. Dispersed storage is also a challenge for some natural sinks, such as soils and oceans, which also require distinguishing stored removed carbon from pre-existing carbon stocks.

Besides differences in reversal risk and monitorability, different sinks have different capacities. Geological reservoirs will be able to store much more CO_2 in a more permanent and verifiable manner than biological reservoirs. **One solution is sink separation (Figure 7): geological CDR balancing geological (fossil) emissions and biological CDR balancing biological emissions**.

Figure 7: Concept of separation of sinks



Emissions of fossil carbon balanced by capture from the air to geological storage



Emissions from land use balanced by capture in land-based sinks

Source: Bellona Foundation (2022)

Types of storage of CO_2

CDR requires that the atmospheric CO_2 is stored permanently. There are several options for CO_2 storage, with varying risk of reversal and ease of monitoring.

Likely to be permanent, easy to monitor

Geological storage is CO_2 injected underground in geological formations such as **retired oil and gas reservoirs, saline aquifers**, or **basaltic rock** is effectively permanent, with a low risk of re-release. While the injection process needs to be controlled and monitored, underground gas injection and storage is a commercialised technology

Mineralized CO_2 is bound into minerals such as basalt, or manmade materials such as concrete, and is only rereleased if exposed to temperatures above 500C (e.g., fire, re-firing in kilns). If the materials are used in buildings, subsurfaces, or other stationary and large-scale applications, they are easily monitorable.

Note: Most manmade materials suitable for mineralization, such as fresh concrete, demolition wastes, lime, slag, and fly ash are materials that originally contained carbon dioxide (e.g. limestone). This CO_2 was released from the material in a conversion process, e.g., steel production, cement production, and typically emitted to the atmosphere. Thus, storing CO_2 in these materials is a remineralization process, and cannot store more CO_2 than was originally released. The emissions from the production of mineralizable materials must be accounted for when calculating the net removal of CO_2 stored in mineralized products.

Potentially permanent but difficult to monitor

Weathering results in CO_2 being dissolved into microscopic molecules, which then leach into the soil and eventually into the ocean or underground aquifers. The CO_2-containing molecules are stable and inorganic and can persist for hundreds or thousands of years as part of the slow geological carbon cycle (though some amount may be taken up by plants or animals). However, as the CO_2 dissolves and disperses, it is very difficult to accurately measure and track.

Biochar stores carbon in pyrolyzed biomass–essentially a form of charcoal. Depending on how the biochar is made, over 90% of the stored carbon can be stable, and is unlikely to decompose for hundreds of years. However, biochar is combustible, and therefore fire represents a reversal risk.

Ocean storage is not treated in this report. It is theorised that CO_2 stored in deep oceans (via weathering, injecting, or biomass sinking) is likely to become part of the ocean carbon cycle, thus storing carbon for hundreds or thousands of years, but there are still many uncertainties and limited possibilities to track and monitor ocean-stored CO_2, which is often disperse.

Requires continuous management to maintain storage

Soil carbon storage is the storage of carbon in soils, such as by application of compost or tilling cover crops into soil. Soil carbon is susceptible to erosion and continuous land management is needed to maintain stocks.

Afforestation is the storage of CO_2 in standing biomass stocks, such as forests. Biomass intended for CDR needs to be managed in perpetuity to prevent re-release of stored carbon due to fire, disease, pests, drought, harvest, or mismanagement.

Temporary durable storage (delayed emissions)

Note: If emission delay is conducted in a controlled manner, where re-release is predictable and managed, it could have the benefit of 'flattening the curve' of emissions, and provide some breathing room on managing the climate crisis by reducing near-term emissions until it is possible to balance their rerelease with additional removals. However, the risks of delayed emissions is that the re-release could happen in an uncontrolled or unexpected manner and that temporary storage will be used to balance fossil emissions that have a permanent impact on the atmosphere. Therefore, **delayed emissions should be treated separately to permanent CDR**.

Biogenic building materials such as timber, can store carbon for decades, and stationery buildings and infrastructure can potentially be easy to monitor, at least during its initial service life. However, the stored carbon risks being re-released during decommissioning/disposal or during fire or other disasters.

Soil carbon and afforestation can also fall into the category of 'delayed emissions', if they are not managed in perpetuity but instead managed for a set length of time (e.g. decades).

Not CO_2 storage

CO_2 reused in consumable products, such as fuels, fertilisers, foodstuffs, beverages, dry ice, precipitated calcium carbonate (used in cigarette papers and medications), solvents, sodium bicarbonate, and other short-lived chemicals and materials. **These products emit their carbon as CO_2 when they are used**.

CO_2 reused in greenhouses is partially absorbed into growing plants, and partly re-released directly into the atmosphere. The carbon in plants is re-released as greenhouse gases (CO_2 and methane) during decomposition or after consumption.

3.3 Ensuring net removals

CDR is resource intensive. Extracting CO_2 from the atmosphere almost always requires more energy and effort than preventing its initial release. CDR systems, particularly those involving biomass, can also have complex greenhouse gas emission profiles, including methane and nitrogen oxides (N2O). Therefore, **it is fundamental to use a 'cradle to grave' system perspective when evaluating the performance of CDR activities**, accounting for all upstream and downstream emissions associated with the supply chains of inputs needed for removal and storage (e.g. energy, mined minerals, chemical solvents, biomass, transport, waste processing), or, in other terminology, including scope 1, 2, and 3 emissions.

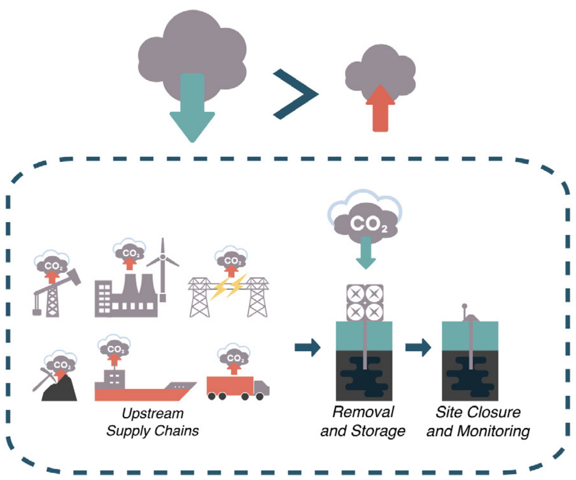
The accounting of CO_2 removal must include not only the physical amount of atmospheric CO_2 permanently stored but also the greenhouse gases (e.g. in CO_2eq) emitted to the atmosphere in the supply chains of the CO_2 removal, transport, and storage processes (Figure 8). This represents the **net removal: permanently stored atmospheric CO_2 minus associated emissions**, as this is the amount by which the CDR process decreases atmospheric greenhouse gases.

CO_2eq

Not all greenhouse gases result in the same amount of global warming. For example, methane has 25 times the 100-year global warming potential than carbon dioxide. This means that for every kilogram of methane released, over the course of a century, it will cause the atmosphere to heat up as much as 25 kilograms of CO_2.

To make it easier to understand and compare the impact of different greenhouse gases, global warming is typically characterised relative to carbon dioxide, in a unit called 'CO_2 equivalent', CO_2eq or CO_2e for short. Most commonly when you see CO_2eq, it is 'CO_2eq-100', which is the global warming impact compared to carbon dioxide on a 100-year time scale. Timescale is important. As we noted, methane has 25 times the global warming potential of carbon dioxide on a 100-year time scale, but 86 times on a 20-year time scale. In contrast sulphur hexafluoride has a global warming potential of 22 800 times that of CO_2, kilogram for kilogram, on a hundred year timescale, but 16300 times on a 20 year time scale. This is because greenhouse gases, like many chemicals released into the environment, behave differently over different periods of time.

Figure 8: CDR must be based on net removals.



A CDR activity decreases atmospheric greenhouse gases not by the amount of CO_2 it extracted from the atmosphere, but by the amount of permanently stored atmospheric CO_2 minus the amount of greenhouse gases emitted in the complete supply chains of removal, transport, and storage processes.

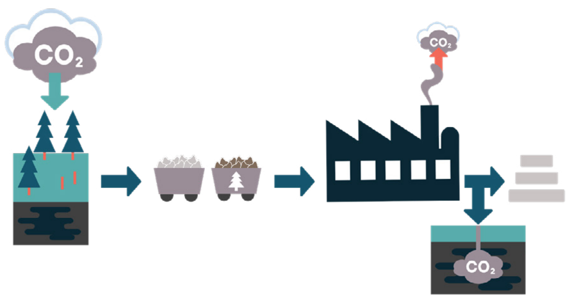
Source: Bellona (2022)

4. Quick scan: BioCCS

This section presents the main results of the data collection process, and assessment of the CDR potential in the wider Amsterdam Metropolitan Area and NSCA, applied to bioCCS options. Annex 7.1 describes the methodology under which the information and data was collected and assessed for the purpose of this report. More comprehensive data collected during interviews with players along the CDR chain are presented in Annex 7.3. The companies interviewed are representative of the types of players present in the area, but are not exhaustive.

Biomass stores carbon from the atmosphere as it grows, but releases it when it decomposes, or is combusted. If the CO_2 is captured, transported and permanently stored, the result is that of a net removal of CO_2 from the atmosphere. **Biomass with carbon capture and storage (bioCCS) are the processes in which CO_2 from biomass origin (i.e. biogenic CO_2 as opposed to fossil fuel origin) is captured and permanently stored** (Figure 9). This can be from any industrial process which uses a biomass-based feedstock resulting in a CO_2 process stream. The CO_2 can then be captured and stored using similar technologies as those associated with conventional CCS (see Sidebar below). BioCCS requires both a source of biogenic CO_2 and a sink to store that CO_2 in. Currently in Europe, ~200 Mt CO_2 per year (5% of of 2018 EU emissions) could be mitigated with bioCCS. With ambitious deployment, BioCCS could have the potential to remove up to 800 Mt CO_2 from the atmosphere every year in Europe by 2050.

Figure 9: Overview of bioCCS pathway



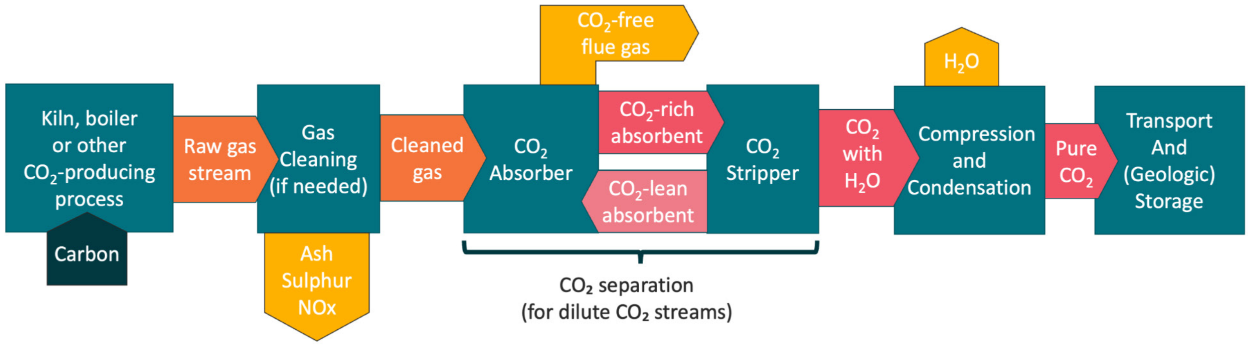
CCS

CO_2 capture and storage (CCS) is a chain of commercialised technologies that separates CO_2 from a gas stream, transports that CO_2 to an appropriate storage site, such as a geologic reservoir, and stores the CO_2 permanently (Figure 10). CCS can be applied to different sources of CO_2, such as the combustion of fossil or biogenic fuels, the calcination of limestone, the fermentation of biomass, methane reforming for hydrogen production (e.g. used for ammonia production), and other chemical processes. A typical CCS process involves several steps:

- **Gas cleaning**: Depending on the composition of the gas stream and the separation technology. used, it may be necessary to remove impurities, such as NOX and SO2, prior to CO_2 separation. Otherwise, the separation equipment, chemicals, or transport vessel could be damaged.
- **CO_2 separation** is needed to separate CO_2 from a mixed gas stream, such as an industrial flue gas (which are typically 5–25% CO_2). There are several methods to do this, but the most common is using a solvent or sorbent that binds with the CO_2, and then releasing the CO_2 from the solvent/sorbent, after which the solvent/sorbent can be reused. This releasing step is responsible for the high energy demand of CO_2 capture, which can range from 2–5 GJ/t CO_2, depending partly on technology but mostly on how dilute the CO_2 is (capturing more dilute CO_2 is more energy intensive).

  Some processes, such as fermentation, produce a pure stream of CO_2, so capture only requires isolating the CO_2 stream, without the need for separation.
- **Compression**: CO_2 is compressed to make it easier to transport. Compressing CO_2 also removes any remaining water mixed in via condensation, which helps prevent corrosion of the transport vessels.
- **Transport**: Unless the CO_2 capture and storage sites are co-located, the CO_2 has to be transported. CO_2 transport can be by pipeline, boat, train, or truck.
- **Storage**: CCS specifically implies geologic storage, which requires site selection, preparation, controlled injection, and monitoring. Empty oil and gas wells are often ideal storage sites, as they are well mapped, may have existing wellheads, and have proven capacity to store gas for millenia. Saline aquifers and basaltic formations are also used as stable storage sites. When properly carried out, geologic CO_2 storage is a safe and well understood process.

Figure 10: CO_2 capture and storage involves a chain of technologies (Modified from Tanzer in DelftX 2022)



4.1 Overview of sources

Table 2 below provides an overview of identified sources of biogenic CO_2, based on the interviews conducted in the scope of this project, also presented in Figure 11. These represent a cumulative ~900,000 t CO_2/year in Amsterdam and the NSCA, representing 5% of total NSCA CO_2 emissions (fossil and biogenic), or 15% of non-Tata Steel related CO_2. It should be noted that this is not an exhaustive list of all the existing emitters of biogenic carbon in the region. More detailed information on each source identified is presented in Annex 7.3.

Figure 11: Maps of the interviewed sources of biogenic CO_2 in the Port of Amsterdam (Source: Google Maps 2022)

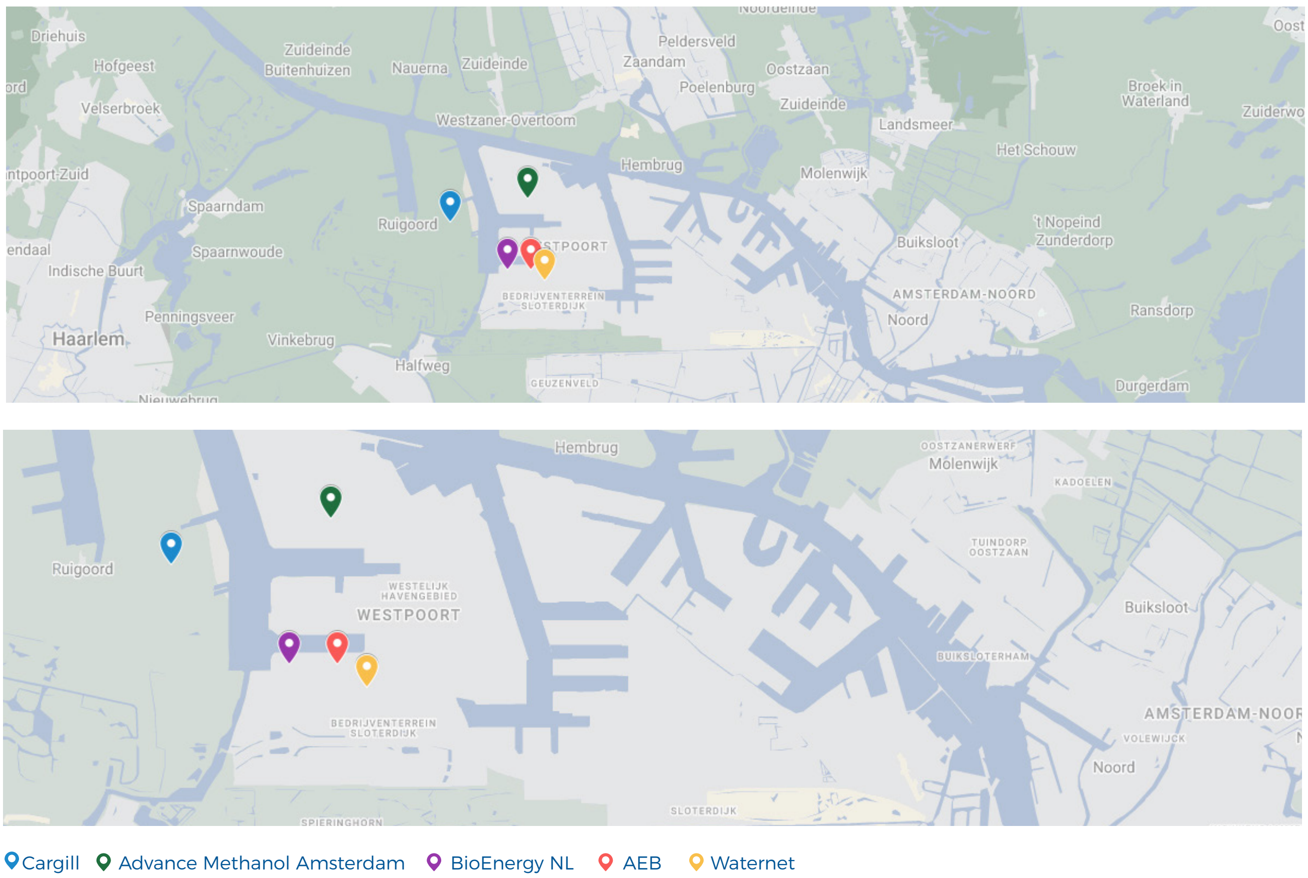


Table 2: Overview of interviewed sources of biogenic CO_2

Note on headers:

- Scale of emissions: volume of biogenic CO_2 which is expected to be emitted, under specified time indication
- Potential by 2030/2050: relates to the potential of the source to emit biogenic CO_2 in Amsterdam and the NSCA by 2030/2050: not promising; less promising; promising; very promising

Name	Description	(Expected) scale of biogenic CO_2 emissions	Potential for capture for CDR purposes by 2030	Potential for capture for CDR purposes by 2050
Advanced Methanol Amsterdam (Gidara Energy)	Production of renewable fuel (methanol) from non-recyclable waste, to be fully operational in 2025. Biogenic CO_2 stream is expected to be transported to greenhouses, but open to geological storage, depending on availability and potential of accessing SDE++ subsidies. Potential future hydrogen production would create additional biogenic CO_2 streams.	116,000 t CO_2/year at operation	**Less promising** Operation will only start in 2025, with initial biogenic CO_2 streams going to greenhouses (driven by summer demand), rather than storage.	**Promising** Volumes of biogenic CO_2 are expected to increase, with the possibility of geological storage as more CCS projects come online thus increasing storage options.
AEB Amsterdam	Waste-to-energy company processing approximately 1.3 million t of waste per annum and producing steam and electricity to be used in both district heating and the surrounding process industries. There is a planned CO_2 capture unit for mixed fossil and biogenic flue gas streams. While ~60% of AEB's carbon emissions are biogenic, it is the largest source of biogenic CO_2 identified in the region.	~660,000 t CO_2/year currently	**Promising** Existing plans for CCS through the Aramis project could become operational by 2028–2029.	**Very promising** Geological storage could account for a greater part of the captured biogenic CO_2 share, as the business model is proved to be viable.
Cargill	Sunflower and rapeseed crusher and refinery for food products, with plans to use cocoa husks (24–25 kt/year) from existing processes to replace natural gas. This will generate a stream of biogenic CO_2, with no plans for capture currently.	~40,000 t CO_2/year by 2025	**Less promising** With the cocoa husk project coming online by 2025 only, and no currently foreseen plans for capture, it is unlikely that this stream can be captured and stored by 2030 unless strongly incentivised	**Promising** It is likely that by 2050, CCS will be more established, in terms of technology and regulations, so that Cargill will explore capturing its biogenic CO_2 to store it permanently.
Future Biogas	Largest biomethane producer in the UK, with a new business model centred on anaerobic digesters, which produce biogenic CO_2 for storage in geological reservoirs. While this is not in the project's geographical zone, similar technologies around Amsterdam could be targeted.	~5,000–15,000 t CO_2/year/plant	**N/a** Not operating in the project area, but similar companies in the area would be promising leads, with biogenic CO_2 streams being directly produced.	**N/a** Not operating in the project area, but similar companies in the area would be very promising leads.

Name	Description	(Expected) scale of biogenic CO_2 emissions	Potential for capture for CDR purposes by 2030	Potential for capture for CDR purposes by 2050
Waternet	Public waste water treatment plant (largest in the Amsterdam harbour area, operating under the regional water authority and the municipality. There are currently no plans to capture and store CO_2 before 2030, but they are piloting green gas installations.	~85,000 t CO_2/year currently	**Less promising** There are currently no plans to capture CO_2 before 2030. Capturing biogenic CO_2 would require a change in process, as Waternet highlights streams are currently too small and too diluted to capture.	**Less promising** With the development of capture technology, it could be expected that Waternet would be able to capture its biogenic CO_2 by 2050.
Bio Energy Netherlands	Bio Energy Netherlands is not currently a source of biogenic CO_2, but is expected to develop into hydrogen production in the NL, including in the Amsterdam region, which would generate streams of biogenic CO_2.	TBC	**Not promising** Not currently producing biogenic CO_2 for use or storage.	**Promising** By 2030, up to 20 gasifiers will be installed in the Netherlands for hydrogen production, which will generate biogenic CO_2 streams. Permanent storage is currently being considered as an option for these CO_2 streams.

Biogenic CO_2 source: combustion of biogenic wastes

Waste-to-energy plants combust residual and municipal waste to generate heat and electricity. The share of waste input into a waste-energy system that comes from biogenic origins will produce biogenic carbon emissions upon combustion.

The waste-to-energy company **AEB** processes municipal waste and sewage sludge and incinerates the residual (non-recyclable) fraction to produce heat and electricity, which is supplied to the surrounding areas. **AEB currently generates ~1.1 Mt CO_2 per year, of which ~60% is of biogenic origin**. As the largest emitter of biogenic carbon in the area, AEB is well-placed to take a central role in demonstrating the potential for CDR in the NSCA. A CO_2 capture unit is already planned, with expected operation in 2028–2029, with a capture capacity of ~450 kt CO_2 per year. This represents ~9% of the City of Amsterdam's entire emissions and is equivalent to the natural gas consumption of two thirds of all Amsterdam households. **The captured CO_2 is intended for use in greenhouses, which would not result in CDR**. However, this CO_2, or CO_2 from an expansion of capture capacity, could be redirected to permanent storage in the future, leading to CDR.

Cargill operates a seed crush process and sunflower refinery plants in Amsterdam and Zaandam, which produces oil for food manufacturers and bottlers. As part of its energy transition plans, Cargill has plans to use waste cocoa husks to replace natural gas for its heat generation. **This process will not only displace emissions from natural gas, but actually generate more biogenic CO_2 emissions – which could be captured –** because of the lower energy density of cocoa husks. There are currently no plans to capture the carbon emissions from the biomass combustion process, with the **lack of infrastructure and insufficient subsidies cited as a key factor**.

The expected scale of captured biogenic CO_2 is currently limited by the capture capacity of AEB's CO_2 capture facility (~450 kt CO_2). It is still unclear how much will be dedicated to use rather than storage, although it can be expected that geological storage will account for a greater part of captured biogenic CO_2 as the business model is proved to be viable.

Key considerations

- **Waste incinerators often represent the largest source of biogenic CO_2 emissions in an urban area**.
- Any considerations of CO_2 capture are **largely driven by cost, including the cost of the input biowaste**, which must be low enough to uphold the business model. Similarly, the choice of offtaker/storage for captured carbon is also financially driven, e.g. based on the availability and amounts of subsidies.
- **Emissions from waste-to-energy plants have a 'block' profile**, by which volumes cannot be ramped up or down. This must be considered when evaluating potential offtakers.
- As the largest source of biogenic carbon in the area, **permanently storing AEB's carbon emissions is an apparent opportunity and should be encouraged**, in particular as it is already connected to the OCAP pipeline.
- Storing biogenic emissions (from all types of sources) requires deployment of **dedicated infrastructure for capture and transport**. Depending on the volume of emissions, this may take different modes of transport, for which any associated emissions also need to be taken into account.

Biogenic CO_2 source: biofuel production plants

Biogas is produced from the anaerobic digestion, or fermentation, of biomass and organic materials. The biogas can be upgraded to biomethane ('green gas') by separating CO_2 and removing other trace gases, typically resulting in a high-purity stream of CO_2. Biogas can be made from a variety of biogenic feedstocks, including waste wood and forest biomass, agricultural waste, or energy crops, such as cereals, maize and grass. **Biomethane production plants are an example of obvious candidates for CDR, as CO_2 separation is a necessary part of the biogas upgrading process**. For biomethane production, CO_2 emissions can be captured at much cheaper costs as they do not require separation from a flue gas stream (**Future Biogas** generates a stream of 98% 'green' CO_2 in its UK operations). Biogas plants can also emit fossil CO_2, e.g. from the use of natural gas or other fossil fuels for energy purposes. Approximately 200 million cubic metres of biogas were fed into the Dutch gas network in 2020.

Advanced Methanol Amsterdam, a project operated by Gidara Energy converts non-recyclable waste, such as certain types of wastewood and municipal waste, into renewable fuels, notably methanol. Due to be operational in early 2025, its **116,000 t CO_2 per year emissions (90% biogenic) will be captured and delivered to greenhouses using the OCAP pipeline, which will not result in CDR**. The use of CO_2 by greenhouses is driven by summer demand and accessibility of SDE++ subsidies. Storing these emissions instead of using them in greenhouses could be an option for the future, depending on how fast geological storage projects come online, the fossil/biogenic fraction of the waste input as well as commercial drivers. This is being actively considered by Advanced Methanol Amsterdam. However, there are restrictions on the fate of the CO_2 (e.g. a minimum threshold must go to greenhouses to fulfil contractual obligations).

Bio Energy Netherlands is expecting to construct 20 gasifiers in the country by 2030 including in Amsterdam, with the aim of producing hydrogen, which will also produce green CO_2 streams. T**he scale of these potential biogenic emissions is currently still unclear**. It is also unclear how much of captured biogenic CO_2 from biofuel production will be earmarked for CCU rather than CDR.

Key considerations

- **Biogas production plants are 'low-hanging fruits' for sourcing biogenic CO_2**, as biogenic CO_2 is generated and purified as part of the production process; this means carbon capture technology does not have to be applied.
- **The sustainability credentials of the biomass sources are critical for the assessment of removed carbon (when the biomass is not a waste)**, with any emissions related to biomass sourcing to be taken into account in full. The use of energy crops may entail additional sustainable development consideration, in case of competition with food crops or indirect land-use change effects.
- The fate of CO_2 between usage and storage is partly determined by demand from greenhouses, the origin (i.e. biogenic or fossil) of CO_2 as well as commercial factors (such as access to SDE++ subsidies).
- **With likely greater demand for hydrogen in the future, further streams of biogenic CO_2 from hydrogen production will be generated**.

Biogenic CO_2 source: wastewater treatment plants

Wastewater treatment plants (WWTP) remove contaminants from sewage waters through physical, chemical and biological processes, so that cleaned water can be released into the environment. Biogenic carbon emissions are generated at various stages of this process, particularly in the water and sludge treatment processes, during which bacteria are fed oxygen in aeration tanks and emit CO_2.

Waternet is a public WWTP, operating under the regional authority and the municipality. Its Amsterdam plant is the largest wastewater treatment plant in the Amsterdam harbour area, serving approximately one million people. Biogenic carbon emissions are generated particularly during: i) the treatment process in which bacteria produce CO_2; ii) incineration of the sewage sludge at the AEB plant; and iii) biogas production. Insights into biogenic carbon emissions are a new topic within the water authority, with methane and nitrous oxide being priorities in the past. **There are currently no plans to capture and store CO_2**, in particular because the CO_2 streams are considered to be too small and diluted in the current process. It is likely that plans to capture and store CO_2 at Waternet will not occur before 2030. **While the financial business case exists for capturing methane from WWTP processes, it does not for CO_2** under the national and EU incentives context.

Rather than capturing carbon, it has been suggested that changes could be made to the water treatment processes to reduce emissions. In general, there remains knowledge and data gaps that need to be addressed for water treatment plants to consider CCS more comprehensively.

Key considerations

- The potential scale of captured biogenic CO_2 for CDR purposes is still unclear.
- While there are a number of biogenic CO_2 streams in the wastewater treatment process, **these are too small and diluted to consider carbon capture**, which would be too costly for this process.
- **More research is needed to fill the gaps in knowledge that remain, notably in terms of the technical and financial viability of fitting CCS infrastructure to existing WWTPs**.
- Any potential sourcing or capture of biogenic CO_2 from WWTPs is likely to occur after 2030.

4.2 Overview of sinks

Table 3 below provides an overview of identified sinks (off-takers for transport and storage) of biogenic CO_2, based on the interviews conducted in the scope of this project. More detailed information on each source is presented in Annex 7.3.

Table 3: Overview of interviewed sinks (including transport) of biogenic CO_2

Note on headers:

- Scale of storage: volume of biogenic CO_2 which can potentially be stored, under specified time indication
- Potential by 2030/2050: relates to the potential of the sink to store biogenic CO_2 from Amsterdam and the NSCA by 2030/2050, if implementation and scaling begins in the near-term: not promising; less promising; promising; very promising

Name	Description	(Expected) scale of CO_2 storage	Potential to store biogenic CO_2 for CDR purposes by 2030	Potential to store biogenic CO_2 for CDR purposes by 2050
Air Liquide	Air Liquide processes CO_2 from emitters. It is only currently connected to large industrial plants, which generate fossil fuel-based emissions. In the future, Air Liquid will to some extent shift to biogenic carbon.	n/a – unclear	**Not promising at present** Air Liquide is not currently focused on biogenic CO_2. While they have the technical expertise and network, it is unlikely that the shift to biogenic CO_2 will occur before 2030.	**Promising** By 2050, it is expected that there will be stronger environmental and regulatory drivers, along with a better-established business case to focus operations on biogenic CO_2.
Mitsubishi Corporation	Mitsubishi Corporation is involved in multiple carbon mineralisation technologies, including: carbonates and aggregates from waste; ready-mix concrete from CO_2; and pre-cast concrete from CO_2. Although not currently operating in the NL, this technology is proven and can be rapidly deployed.	n/a – unclear	**Less promising** Carbon mineralisation in building products can be implemented relatively quickly, if the biogenic CO_2 inputs can be sourced. In some cases, atmospheric CO_2 can also be used as inputs. However, the scale of CDR achieved is likely to be relatively small.	**Promising** It is expected there will be more readily available sources of biogenic CO_2, though likely that only limited volumes would be used for mineralisation in building products in the project area.
OCAP	OCAP is a transporter and supplier of CO_2, especially to greenhouses in the south of the NL, via its own pipeline. Delivery for other applications often proves to be difficult, given the small purchase volumes and the high quality CO_2 that is required.	n/a – transport only (transports 600,000 t CO_2/year)	**Promising** OCAP is the only existing pipeline network connecting Amsterdam to the CO_2 storage infrastructure in the Port of Rotterdam. As such, it is a central element of the CDR supply chain in the short-term. It is already connected to sources of biogenic CO_2, but currently for use rather than storage. Smaller volumes of biogenic carbon could be rerouted to permanent storage.	**Very promising** With developing and expanding legislation and regulation on CDR, it can be expected that OCAP will expand its capacity to accommodate a larger share of its CO_2 to geological storage projects in the Port of Rotterdam.

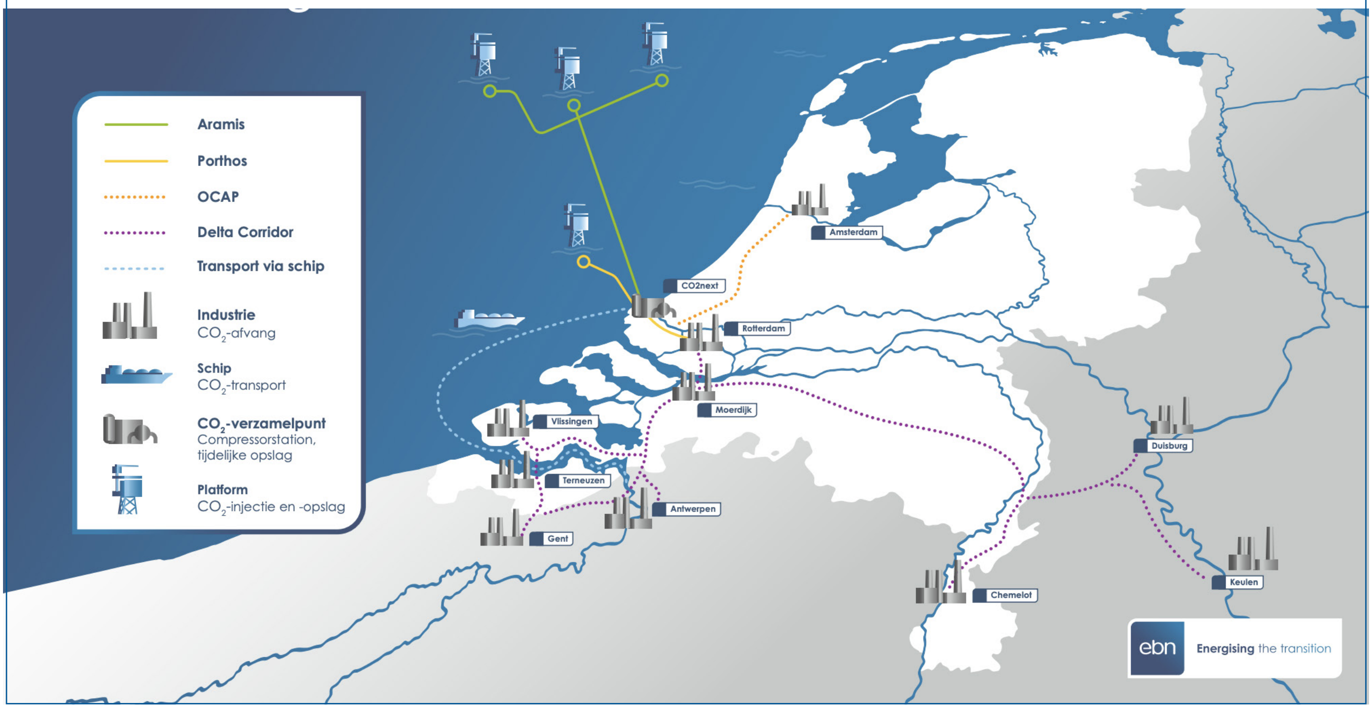
Name	Description	(Expected) scale of CO_2 storage	Potential to store biogenic CO_2 for CDR purposes by 2030	Potential to store biogenic CO_2 for CDR purposes by 2050
Porthos	CO_2 from industry is transported by pipeline to the Port of Rotterdam and through an offshore pipeline to a platform in the North Sea, approximately 20 km off the coast. From this platform, the CO_2 will be pumped into an empty gas field, in a sealed reservoir of porous sandstone more than 3 km beneath the North Sea.	2,500,000 t CO_2/year for 15 years (exp. start in 2025)	**Not promising (sold out)** Porthos will be operational from 2025 and permanently store vast quantities of CO_2. However its current capacity is already fully sold out for storage of fossil emissions – additional storage options need to be developed.	**Less promising** Porthos is intended to be decommissioned by 2050, and the currently foreseen storage capacity is already sold out.
Aramis	Similarly to Porthos, CO_2 from the Port of Rotterdam will be transported by pipeline to an offshore platform ~200 km off the coast. The CO_2 will then be injected into the gas field 3-4 km below the seabed.	5,000,000 t CO_2/year initially (exp. start in 2027–2028) Full capacity: 22,000,000 t CO_2/year	**Very promising** Aramis should be operational by 2030 and may include biogenic carbon.	**Very promising – TBC** Aramis will store millions of tonnes of CO_2 per year. It is likely that clients will include providers of biogenic CO_2, leading to carbon removals.
Sika	Technology to convert concrete demolition waste (CDW) into carbonated cement stone and aggregates for further construction. Pilot plant to prove concept; technology can then rapidly be deployed.	20–60 kg CO_2/ t CDW; 100–200 t CDW/hour	**Less promising** Although not implemented in the project area at the moment, this type of technology can be deployed relatively quickly, depending on availability of inputs (CDW).	**Promising** If located near an input source (concrete/demolition waste), there is high potential for this type of technology.

Biogenic CO_2 sink: geological storage

Geological CO_2 storage – such as in depleted oil and gas fields – is one of the most durable forms of carbon storage, with limited risk of reversal. This process involves injecting captured and compressed CO_2 into existing geological reservoirs. It is particularly relevant for the Netherlands and for Amsterdam, which are in relatively close proximity to a number of such depleted reservoirs under the North Sea. The offshore storage capacity is expected to be in the range of 100s Mt CO_2 (conservatively), up to 1 Gt CO_2. This storage capacity has great potential to be used, considering existing oil and gas infrastructure and the location of industrial clusters along the coast. In fact, multiple initiatives are already underway to exploit this potential.

Porthos, which has been interviewed in the scope of this project, is one such example. Currently nearing final investment decision, Porthos is expected to become operational in 2025, and will inject 2.5 Mt CO_2 into permanent geologic storage every year for 15 years, in a gas field only 20 km from the coast of Rotterdam (Figure 12). However, this storage capacity is already sold out and committed to four large industrial clients. While the pipelines from the Port of Rotterdam have higher capacity, more storage sites need to be developed to store larger volumes of CO_2. The capital expenditure for Porthos was covered by state-owned entities, namely the Port of Rotterdam, GasUnie and EBN. The cost for transportation and storage, however, although dependent on the volumes of CO_2, is EUR ~50/tCO_2, not accounting for the cost of capture, which can reach upwards of EUR 100/tCO_2.

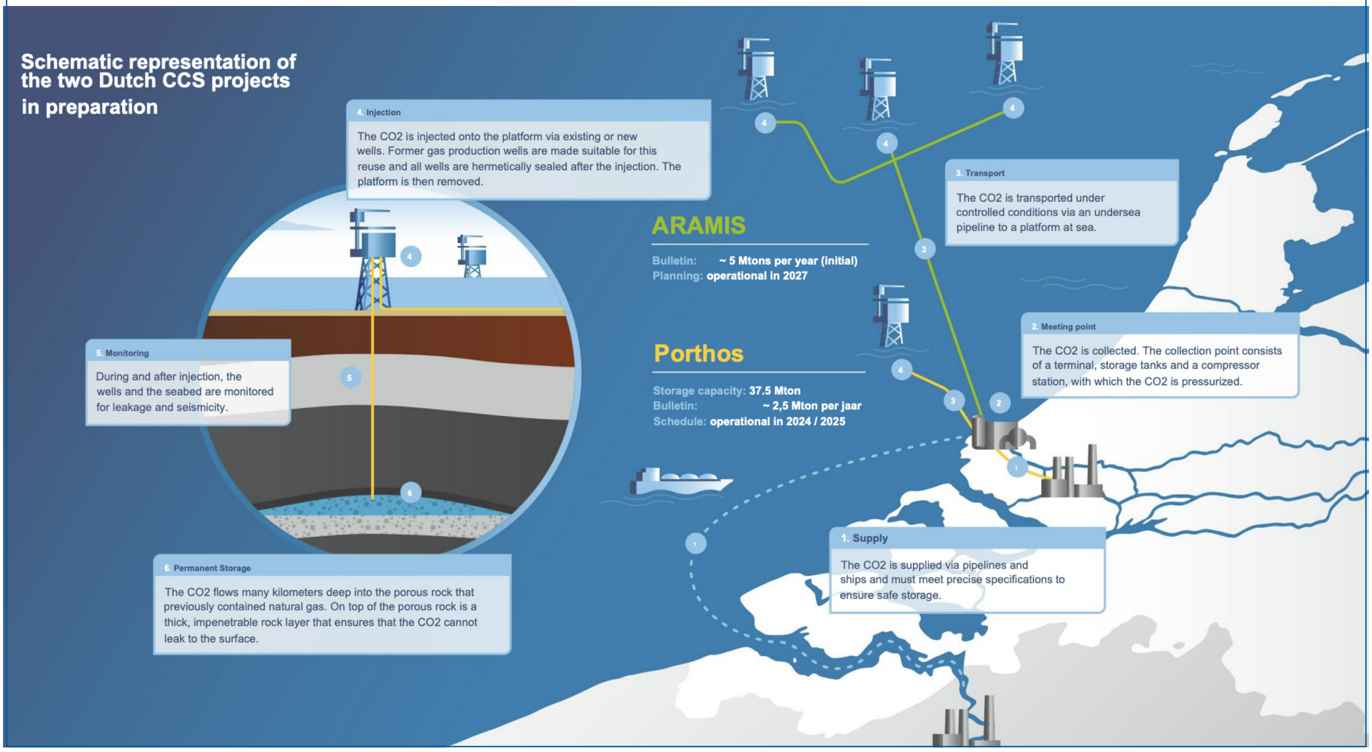
Figure 12: Map of CCS infrastructure in the Netherlands and beyond, including Porthos, Aramis and OCAP



Source: EBN whitepaper, 2022

A second geological storage initiative, **Aramis**, aims to **increase the scale of CO_2 storage by 5 Mt CO_2/year initially – 22 Mt CO_2/year at full capacity –** by accessing another depleted gas field approximately 200 km from the coast. It is currently still in a design and permit process phase, and not expected to become operational before 2027. Porthos and Aramis are **essential to demonstrate the feasibility and viability of geological storage under the North Sea** (Figure 13). Additional demand for geological CO_2 storage will undoubtedly lead to the preparation of additional storage fields. Both Porthos and Aramis make use of CO_2 transport and storage infrastructure located in the Port of Rotterdam. This should still be of great interest to the City of Amsterdam, as **the existing OCAP pipeline links the two areas, giving access to the Porthos and Aramis facilities**. A third project – **Athos** – was planned to be implemented in Amsterdam, but was cancelled; however the development of CO_2 infrastructure in the North Sea Canal area remains an interesting opportunity for the future.

Figure 13: Illustration and description of Porthos and Aramis projects



Source: EBN, 2022

Key considerations

- **There is huge carbon storage potential under the North Sea**, presenting the opportunity for CDR at scale for the Netherlands. Offshore storage capacity near Eindhoven is at least in the range of 100s Mt CO_2, but could be as large as 1 Gt CO_2 – this is as much as over 50 years of storage of the NSCA's current annual emissions.
- **Accessing these storage sites will require the development and extension of infrastructure** (particularly pipeline) networks; currently, only the OCAP pipeline links the NSCA to the Port of Rotterdam.
- The first geological storage projects are due to come online in the next few years, **offering proof-of-concept** and viability for development of additional decommissioned gas fields.
- Other storage sites, located beyond the Extended Economic Zone of the Netherlands such as in the UK or Norway, would likely have available storage capacity before 2030.

Biogenic CO_2 sink: carbon mineralisation in durable products

Carbon mineralisation in durable products, such as construction materials, is another option for durably storing carbon. For example, **Sika**'s reCO_2ver technology, which uses concrete demolition waste (CDW) as an input, produces cleaned aggregates and carbonated cement stone, which can then be used in new constructions. **CO_2 is sequestered in CDW in an accelerated chemo-mechanical process, producing carbonated limestone powder**. Furthermore, **the use of this output to replace conventionally-produced materials reduces the amount of cement or clinker required in concrete production**.

It should be noted that the **CO_2 stored in aggregates is replacing the CO_2 emitted from the production of cement**, which is made by removing CO_2 from limestone. Therefore, the origin and emission profile of the storage material must be carefully considered. Concrete and CDW will also naturally mineralize some atmospheric CO_2, without the need for additional energy input. However, this process is very slow for fresh concrete, as it is dependent on exposed surface area; over the lifetime of a building, no more than 10–20% of CO_2 emitted by limestone during cement production will be absorbed.

While neither of the two carbon mineralisation companies interviewed in the scope of this project currently operate in the NL, their solutions are technologically-ready and are able to be implemented relatively quickly, with new plants taking approximately one year to construct. **The scale of removals that these opportunities could generate is, however, unclear, and very much dependent on the size and number of plants constructed**. Sika's pilot plant removes between 20–60 kg CO_2/t CDW (or 2–12 t CO_2 per hour) when in operation, depending on the input flow and age of the CDW; similar ranges could be expected if applied in the NL. **Costs are similarly unclear**; Sika's pilot plant is complicated as it performs the whole process in one step, but could be operated with design changes for ease (and associated cost reduction) and scalability.

While not interviewed for the purpose of this project, ENCI IJmuiden is one of the only two remaining cement production sites in the Netherlands, and so a promising site to apply carbon mineralisation technologies. Depending on the specific technology, carbon mineralisation can make use of atmospheric CO_2, biogenic CO_2, or flue gas directly. The process would not be considered to be removing carbon if using flue gas, but **interviewees have noted that it is difficult to secure biogenic CO_2**. Transport of the captured carbon by truck, barge and rail are likely to be the dominant mode of transport. Pipelines could also be appropriate in industrial areas, although concrete production is often decentralised, making pipeline connections less likely.

The potential for CO_2 storage through carbon mineralisation is still unclear, but is expected to be in the 10s kt CO_2 per year.

Key considerations

- **Carbon mineralisation technologies can easily be deployed**, though location (e.g. nearby cement or concrete demolition plants) is key for access to inputs – available space to transport and store materials also needs to be considered.
- **Regulations and standards for construction materials**, which can be very conservative, may hinder the deployment of recycled concrete, even though it is a relatively low-cost solution, which could already generate CDR.
- The scale of removals achieved is directly related to: i) the number of plants made operational; ii) the amount of available materials, limited by the amount of local demolition wastes; and iii) the demand for materials such as recycled concrete.
- The **increase in sales price of these products**, compared to conventional concrete products can be up to two- or three-fold.
- Municipalities can play an important **role in encouraging carbon mineralisation in construction products through public procurement**, and e.g. mandating minimum thresholds for the use of recycled concrete in new constructions.

4.3 Overview of transport options

Transport from biogenic CO_2 sources to permanent storage is an essential part of bioCCS. CO_2 transport options include trucks, rail and ships for liquified CO_2 and pipelines for gaseous CO_2.

Pipelines are an efficient modality to transport CO_2 from its source to storage locations, particularly for larger sources of CO_2. Pipelines also offer the possibility of different sources to connect to the same CO_2 transport network, as long as certain quality requirements are met. However, their construction is expensive and the network is currently limited. **OCAP** is the most important CO_2 transport player in Amsterdam. **OCAP makes use of the pipeline connecting Amsterdam to Rotterdam to provide ~600,000 t CO_2 per year to greenhouses**. As such, it is currently the only connection between the Amsterdam area and the underground storage opportunities in the North Sea. **The sales price to customers operating greenhouses is ~EUR 60/t CO_2 –** this represents the cost per tonne for transport only, not accounting for capture or storage. OCAP's supply capacity to greenhouses is expected to reach 2,000,000 t CO_2/year by 2030, but demand is highly seasonal.

In situations where CO_2 sources are highly decentralised or smaller, pipelines will not be appropriate or economically-feasible. The captured carbon therefore has to be processed and liquefied for transport by truck or ships or train. The CO_2 liquefaction process has high energy requirements and more expensive processing costs than that of gaseous CO_2. However, it offers the possibility of more distributed, higher-quality and more efficient offtakes. These options were not explored in the scope of this project.

Key considerations

- **An extensive CO_2 transport network is essential to unlocking decentralised carbon removals**, but plant operators may not have the finances to invest in such a network.
- There is a **public role in facilitating the construction of such a CO_2 collection infrastructure** in the same way as other public infrastructures such as water and electricity are financed or deployed through regulated assets.
- **OCAP remains the only available pipeline to access the CO_2 hub in the Port of Rotterdam and geological storage in the North Sea.**
- It is unclear how much of OCAP's transport capacity will be dedicated to carbon storage rather than use.
- **Each transport modality is associated with its own emissions,** which must be taken into account when measuring net removals.
- CO_2 transport as a service is being deployed on inland waterways and the seas, offering potential opportunities for biogenic point source emissions at facilities along the NSCA.
- Additional research must be undertaken to evaluate the potential of transport of liquefied CO_2 by truck, rail and ship.
- Transport by e.g. truck may lead to increased congestion.

4.4 Summary of bioCCS pathways

The bioCCS pathway to achieve CDR is unachievable without three essential components: i) a source of biogenic CO_2; ii) a mode of transport for the CO_2 to go from source to sink; and iii) a storage solution to durably store the CO_2. Figure 14 provides a summary of the main options identified at this stage for each of these components.

Figure 14: BioCCS requires a chain of technologies that capture, transport, and permanently store biogenic CO_2.

Step 1: Biogenic CO_2 source

Waste-to-energy
Biogas production
Wastewater treatment

+

Step 2: CO_2 transport

Pipeline
Trucks
Ships
Rail

+

Step 3: Permanent CO_2 storage

Geological reservoirs
Mineralisation

Waste-to-energy plants, notably AEB, provide the most appropriate source of biogenic CO_2 to date: large streams of CO_2 are produced, a high proportion of which are biogenic, at a predictable and consistent rate. **The scale of AEB's emissions – the largest in the area – make its capture, transport and offtake cheaper and easier to implement**. Biomethane production is also an appropriate source of carbon for bioCCS pathways, as it involves the generation of a high-purity CO_2 as a by-product. While these are much more distributed, and their scale much smaller, biogas producers could provide CDR 'quick wins'. **Green hydrogen production is expected to be a significant source of biogenic CO_2 in the future, whereas WWTPs are unlikely to provide a usable source of biogenic carbon before 2030**.

Carbon mineralisation in building products is limited by the scale of concrete production and demolition in the NSCA, as well as the type of concrete used. Regional data were unavailable, but the remineralisation potential for concrete wastes in the Netherlands as a whole, is unlikely to exceed 1 $MtCO_2$/year. Given the relative ease with which this technology can be deployed and the co-benefits of reducing demand for CO_2-intensive fresh concrete production, remineralisation is still an important technology of interest to both accelerate the deployment of CDR and reduce construction-sector emissions. Additional data are needed to more comprehensively assess the potential of mineralisation in products.

Geological storage remains the most appropriate storage option for bioCCS, providing large-scale permanent storage, just off the coast of the Netherlands. The Netherlands is indeed well placed to access empty gas fields, with a storage capacity which can increase with demand for the foreseeable future, and existing oil and gas infrastructure which can be repurposed. The infrastructure for geological storage is still limited, but **the success of projects such as Porthos and Aramis will be a considerable signal for industrial actors to move in the same direction** – both in terms of better valuing the capture of (biogenic) CO_2, and in exploring and commissioning additional storage sites.

Linking these biogenic CO_2 sources and sinks will require the development of an extensive infrastructure network, both for processing and transporting CO_2. Pipelines have been identified as the most appropriate mode of transport for large scale bioCCS, particularly because this is the main modality linking Amsterdam to the CCS infrastructure and geological storage opportunities in the Port of Rotterdam. **While it is very expensive to extend the existing network, the system is in principle scalable as demand increases**. As decentralised bioCCS requires additional widespread pipeline connections, it is likely that – to a lesser extent – transport of liquefied CO_2 by truck or ship will also increase.

4.4.1 Barrier analysis

Based on the interviews conducted with biogenic CO_2 emitters and offtakers, a range of barriers were highlighted that hinder the development and deployment of bioCCS, in the region and beyond. The below subsections contain details on each barrier, directly informed by the responses provided by interviewees.

- **Regulatory barriers:** lengthy processes permitting and end-of-waste status
- **Policy barriers:** absence of CDR-specific targets and legislation
- **Financial barriers:** insufficient incentives to deploy bioCCS at scale
- **Infrastructure barriers:** lack of accessible transport networks and long lead time
- **Public perception barriers:** public awareness and acceptance, e.g. on mitigation deterrence and sustainability credentials of non-waste biomass

Regulatory: lengthy processes for permitting and end-of waste status

A key barrier to capturing biogenic CO_2 in the Netherlands concerns the attainment of necessary permitting and the so-called end-of-waste status. When a waste stream receives the end-of-waste status, it is no longer considered waste and no longer has to comply with waste regulations. In order to capture biogenic CO_2 from an industrial process for CDR purposes, the emission must be given the end-of-waste status. This barrier was identified by a number of emitters, including Air Liquide, Advanced Methanol Amsterdam, AEB, Waternet and Bio Energy Netherlands – the latter even highlighted this as the most important barrier to bioCCS development. Companies are issued permits based on their specific activities; to expand activities to CO_2 capture, additional permits are required, the process for which can take up to a year. Furthermore, these permits may have associated caps or maximum ceilings on CO_2 volumes. Regional authorities (e.g. NSCA Environmental Service) have the right to make rulings on decisions to provide permits, e.g. for end-of-waste status or CCS activities. However, with no comprehensive CCS national legislation, these entities do not have a clear indication of what position to take on the subject. Specific licences are provided based on intended use, which may vary widely. The recognition of collected CO_2 as a waste stream is a particular issue, as it entails additional permitting requirements.

Policy: absence of CDR-specific targets and legislation

In the Netherlands climate agreement, there are no regulatory targets for CDR. Moreover, there is no differentiation between CCS and CDR. Both are considered under regional and national industrial decarbonisation strategies and are described as a potential solution, though a maximum cap of 8.7 Mt CO_2 has been placed on CCS – the full capacity of the Aramis project already exceeds this cap. Geological storage options, such as the Porthos and Aramis projects, are also hindered by legislation, for example on the nitrogen deposition issue in Natura 2000 areas. A supreme court ruling is expected on whether Porthos falls under government exceptions for nitrogen deposition. An unfavourable ruling would translate into additional permitting requirements and time before commissioning.

The Netherlands would benefit from establishing an additional and separate target to remove carbon from the atmosphere with bioCCS and DAC and storage both in the short- to medium-term and as a clear component of net-zero targets. This would send a clear signal to the market as well as assuage potential concerns of mitigation deterrence expressed by civil society regarding BioCCS and DACCS.

Furthermore, emissions of biogenic CO_2 are currently not accounted for and are not subject to emission caps or taxes. The absence of valuation of biogenic CO_2 (both in liability for emission or compensation for storage) is a barrier to bioCCS.

Financial and market: insufficient incentives and limited demand

Financial and market barriers also hinder the deployment of CDR in the region and in the Netherlands more generally. Particularly, emitters of biogenic CO_2 are discouraged to capture their emissions for CCS and CDR because of insufficient incentives for such activities, leading to poor business cases and projects not being initiated. This was notably highlighted by AEB. Although the SDE++ subsidy is in place, it is not attractive for many players whose activities fall within gaps in the subsidy. SDE++ targets existing infrastructure rather than new infrastructure, and for specific uses. For example, waste-to-energy processes are not eligible under the subsidy, although SDE++ now covers certain low-carbon processes with CCUS. In the case of CCS, the production limit for 2022 is 5.3 Mt CO_2 per year over 15 years. This adjustment was made as CCS is described as 'sufficiently stimulated'. Regarding EU incentives, the historically low carbon price of the EU ETS has been a major barrier for fossil-based CCS; biogenic CO_2 is not covered by the EU ETS at all.

As well as subsidies, the market for CO_2 is, to date, relatively small. In the NL, it is dominated by demand from greenhouses. Without credible incentives, the case for storing biogenic emissions rather than using them may not be strong enough.

Infrastructure: lack of accessible networks and long lead time

Limited infrastructure – particularly transport infrastructure – impedes faster deployment of capture and storage of (biogenic and other) CO_2. Large-scale sources of biogenic carbon are most appropriately transported by pipeline and stored in geological storage, which is dependent on a very small number of stakeholders, namely OCAP, Porthos and Aramis. OCAP is currently the only pipeline linking Amsterdam to the larger CO_2 infrastructure hub in Rotterdam, and is majoritarily focused on CO_2 usage in greenhouses rather than storage. Individual projects are generally unable to finance the required CO_2 collection and disposal infrastructure. Additional connections would be needed to connect further CO_2 sources to existing pipelines for more decentralised removals. Expanding the pipeline network requires huge investments, which may only be feasible if sourcing carbon streams in large quantities.

Porthos and Aramis will be the first two large-scale carbon storage initiatives in the NL, the former taking five years to plan and two years to build. Since the SDE++ started to include CCS, there has not yet been enough time for the development, construction and commissioning of new projects. Similarly, while many offshore gas field operators are working towards permit applications for storage, this is also likely to take significant amounts of time. Once the infrastructure to transport and store large volumes of CO_2 is in place, the bioCCS pathways – logistically and financially – will be clearer and more attractive for emitters. Conversely, the availability of CO_2 is needed to signal the need for investments in transport and storage infrastructure.

Public perception: NGOs and social acceptance

BioCCS and CDR may be perceived as mitigation deterrence, distracting from essential emission reductions. Other concerns include the relative novelty of the technologies, the perceived competition of CCS biomass inputs with food production and other land uses, or the prioritisation of nature-based solutions over 'engineered' solutions. Issues of social acceptance have led CCS projects in the past to be cancelled. However it has been noted that a lot of research on CCS has since been done in the Netherlands (e.g. this recent study), and it is generally well-received by the general public.

As a nascent sector, bioCCS and CDR are complex subjects, on which politicians are not well-versed and the general public lacks awareness. Concerns are still being strongly raised about possible mitigation deterrence and other environmental impacts of CCS by some CSOs and NGOs, such as Greenpeace. While there is motivation from the public sector on bioCCS projects, interviewees have noted that this is not translated into actual concrete support, with no formal positions taken on CCS or CDR.

4.4.2 Potential enablers for bioCCS development

Legislative and regulatory drivers:

- **Streamlined permitting process:** National legislation is needed on the end-of-waste status to enable regional authorities to take a clear position on the issue.
- **CDR-specific policy and targets:** CCS- and CDR-specific policy targets (at municipal, regional and national levels), to encourage development and send clear signals to industrial players operating along the supply chain (biogenic CO_2 supply, demand and transport), both in the medium and long term.
- **Clarified role and use of CDR:** A clear CCS and CDR roadmap, detailing the sequencing for their development, including target industries, use case and geographic scope would provide industry with the foresight required for long-term planning.

Financial drivers:

- **Infrastructure development:** Public intervention may be needed to finance – and/or invest in – infrastructure as a public good (akin to waste collection or sewage processing) to unlock decentralised biogenic emission sources for CDR. Infrastructure development may well be led by emitters of fossil CO_2 for CCS purposes; once existing, the infrastructure could similarly be used by emitters of biogenic CO_2 for CDR purposes.
- **Increased demand:** The fate of the carbon produced (i.e. emission vs storage vs use) is largely determined by the demand for biogenic CO_2, the valuation of carbon and the ease of access to use or storage sites.
- **Higher subsidies:** Financial support through higher, and more comprehensive, subsidies committed to for the longer-term, particularly as relating to the storage element, for a stronger business case.
- **Valuation of CO_2:** Valuation of CO_2 can be a sustainable driver for investment, as CDR project operators can monetise removals on international carbon markets to enable buyers to meet obligations.

Other drivers:

- **Transparency:** Transparency in communicating the envisaged role of bioCCS in the municipal and regional strategies, to industrial players, civil society and the general public, to raise awareness, improve social perception, and ensure inclusivity.
- **Stronger political support:** At the municipal, regional and national levels. Municipal support for CDR-related solutions, including through e.g. investment, public procurement policy and support for pilots. Stronger support should be provided, with formal positions taken on CCS or CDR.
- **Pilot projects:** Pilot projects to test/ demonstrate the technical and financial viability of bioCCS activities could serve to fill existing knowledge gaps.
- **Research and data:** Filling the data knowledge gaps – e.g. conducting full LCAs for processes – would help emitters understand the full picture of the net reduction or removal potential for CCS and CDR and assess their options accordingly.

4.5 BioCCS options summary

Several bioCCS pathways exist, comprising a capture stage, transport stage and storage stage. Identified opportunities are summarised below.

Biogenic CO_2 capture:

Combustion of biogenic waste (AEB; Cargill): Waste-to-energy plants which combust municipal waste for heat and electricity.

• Large biogenic emissions • Existing infrastructure network	• Existing usage in greenhouses • Trade-offs with CO_2 for CCU

Key challenge: Financing infrastructure for CCS → Large investments for carbon capture and expansion of carbon transport network

Biofuel production plants (Advanced Methanol Amsterdam; Future Biogas; Bio Energy Netherlands): Biogas produced from fermentation of biomass; biomethane production already involves separating CO_2 .

• Low-hanging fruit • Increased supply expected with H_2 production	• Depending on input, competition for land-use • Trade-offs with CO_2 for CCU

Key challenge: Sustainability credentials of non-waste biomass sources → Full LCAs required

Wastewater treatment plants (Waternet): Treating wastewater and sewage sludge, with multiple streams of biogenic CO_2 generated.

• Steady supply of CO_2 • Pilots planned for green gas	• Relatively small CO_2 streams • Knowledge and data gaps

Key challenge: Capture not financially viable → Knowledge building to fill gaps

CO_2 transport:

Pipeline (OCAP): Transport of gaseous CO_2 via pipeline infrastructure.

• Connection to CO_2 hub in Rotterdam • Ease of transport for large volumes	• Costs of expanding network • Trade-offs with CO_2 for CCU

Key challenge: Limited and expensive infrastructure network → Financial incentives to increase demand for CO_2 transport

Rail, trucks and ships: Transport of liquefied CO_2 via trains, trucks and ships.

• Possibility of decentralising bioCCS	• Expensive liquefaction process

Key challenge: Cost of liquefying CO_2 → Process learning and innovation

Permanent CO_2 storage:

Geological storage: Storing CO_2 underground in e.g. offshore depleted oil and gas fields.

• Very limited risk of reversal • Massive storage opportunities in North Sea	• Currently limited number of projects • Costly expansion of pipeline infrastructure

Key challenge: First project only coming online in 2025 (and sold out) → Proof-of-concept leading to development of additional storage sites

Carbon mineralisation in durable products: Storing CO_2 in long-lived products e.g. construction materials.

• Easily deployed • Contributes the decarbonisation of a hard-to-abate sector	• Increase in sales price of mineralised products vs conventional • Availability of biogenic CO_2

Key challenge: Unclear scale of removals possible in the region → Knowledge building to fill data gaps

5. Quick scan: Standalone CDR

This section presents the main results of the data collection process, and assessment of the CDR potential in the wider Amsterdam Metropolitan Area and NSCA, applied to standalone CDR options (Table 4). Annex 7.1 describes the methodology under which the data was collected and assessed for the purpose of this report. More comprehensive data collected during interviews with players along the CDR chain are presented in Annex 7.3. The companies interviewed are an indicative representation of the types of players present in the area, but are not exhaustive.

BioCCS is one of several CDR technologies. The advantage of bioCCS is that it is particularly suited for dealing with industrial CO_2 emissions that are already biogenic or cannot currently be abated by other means, such as electrification using renewable energy, or switching to carbon-free processes and feedstocks. However, there are other CDR activities that could be used to supplement bioCCS. These include: direct air capture with storage; enhanced weathering of minerals; accelerated carbonation of mineral wastes; soil carbon storage; biochar; and afforestation. Each of these is presented briefly below, including their mechanism of action, primary considerations for implementation, and the available data for the Amsterdam context.

Five interviews were conducted with stakeholders involved in non-bioCCS CDR, including one each with stakeholders involved with biochar, enhanced weathering, direct air capture, soil carbon storage, and mineralization of demolition wastes. The early state of development of these CDR technologies make it difficult to quantify or assess their realistic regional removal potential. In particular, **for all of the standalone CDR options, long-term real-world studies on removal rates, storage permanence, and co-effects are lacking**. While geologic or mineral storage of gaseous CO_2 is likely to be effectively permanent, some CDR options have higher (afforestation, soil carbon storage) or uncertain (biochar, enhanced weathering) risks of reversal that must be considered, as re-emission of stored CO_2 must be accounted for.

Table 3: Overview of interviewed standalone CDR options

Note on headers:

- Scale of removals: volume of atmospheric CO_2 which can potentially be removed, under specified time indication
- Potential by 2030/2050: relates to the potential of the CDR option to remove CO_2 from the atmosphere – in Amsterdam and the NSCA, specifically – by 2030/2050, if implementation and scaling begins in the near-term: not promising; less promising; promising; very promising

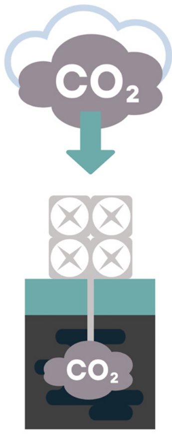
Name	Description	Potential scale of removals	Potential for large-scale implementation by 2030	Potential for large-scale implementation by 2050
Biochar (Bio Energy Netherlands)	Pyrolysed biomass, which is then buried or used as a soil amendment.	Bio Energy Netherlands currently produces 1 kt per year biochar from 2 gasifiers, currently sent to landfill, roughly translating to 3,000 tonnes of CO_2eq removed.	**Less promising** Biochar's legal status is currently unclear and substantial uncertainties remain on its impact on soil, as well as risk of reversal (e.g. from fires).	**Less promising** If biochar does not prove to have any unanticipated negative impacts and sustainable biomass stocks are available, quality-regulated biochar has the potential to be a flexible carbon storage option if it is stored in bulk (e.g. buried), and is a co-product of biosyngas, which can be used both as an energy source and feedstock for platform chemicals. However, if biochar is used only as a soil amendment, then total potential is limited, with an application rate of 20 tonnes per hectare, resulting in total storage potential of 2 Mt)
Enhanced Weathering (CNI)	Ground silicate minerals spread on large surfaces to increase their rate of CO_2 dissolution to a period of years or decades.	Currently zero. CNI estimates a cumulative maximum potential of 1 Mt within the Amsterdam municipality, requiring almost 1 Mt of ground olivine.	**Not promising** Enhanced weathering requires the grinding and transport of large quantities of minerals and application over large quantities of land. Even if applied at scale before 2030, it would take years to decades for removal of CO_2 to accumulate.	**Less promising** Due to the slow uptake rate, enhanced weathering would require large-scale application before 2030 to see appreciable removal in 2050. Even with high application rates, density of removal is low (65 tonnes of olivine per hectare leads to cumulative maximum removal potential of 78 tonnes of CO_2).
Direct Air Capture and Storage (Carbyon)	The use of fans, chemicals, and energy to extract atmospheric CO_2 into a solvent or sorbent, after which it is transported and stored permanently, e.g., in a geological formation	Currently zero. Carbyon has a 1000 t CO_2 per year Netherlands pilot planned for 2024, with an ambition to scale to 1 Mt CO_2 by 2030.	**Not promising** Needs to improve energy efficiency and cost; main focus is on CCU (business case)	**Promising** This could be a promising option for decentralised CDR, if improvements are made on the energy efficiency of the process, conditional on an abundant supply of clean energy and subject to demand competition. It could also be located close to offshore geologic storage.

Name	Description	Potential scale of removals	Potential for large-scale implementation by 2030	Potential for large-scale implementation by 2050
Soil Carbon Storage (Wij.land)	Increasing organic carbon content of soil through land management practices that must be indefinitely maintained.	Unknown. Wij.land estimates a potential removal rate of 1 t CO_2 per hectare per year, which could lead to a maximum removal rate of 35,000 t CO_2 per year in the area. Soil carbon storage is subject to sink saturation and a higher risk of reversal.	**Not promising** Soil carbon storage requires further work to tailor both land management and monitoring practices to regional soils, as well as the need to convince and compensate farmers for changing agricultural practices.	**Less promising** Soil carbon storage has a higher associated risk of sink saturation and reversal. The density of removal is also low. However, land management practices that lead to increased soil carbon have ancillary benefits on land quality and resilience.
Afforestation	The deliberate cultivation of long-term biomass stocks that are indefinitely maintained.	Unknown. Temperate afforestation can remove 2.5–25 t CO_2 per fully-planted hectare per year. Afforestation is subject to sink saturation and a higher risk of reversal.	**Less promising** Even with widespread deployment, newly planted trees have a low initial uptake rate and the density of removal is very low.	**Less promising** With climate-adaptive species selection and continuous maintenance, biomass carbon stocks could be greatly increased in the next thirty years, but is land-intensive and reversal risks must be well managed.

5.1 Direct Air Capture and storage

Direct air capture removes CO_2 directly from ambient air using chemical (or mineral) solvents or sorbents and a lot of energy. The CO_2 is then separated from the chemicals and sent to geologic or mineral storage (Figure 15). Direct air capture is a new technology, with the largest plant capturing and storing 4,000 t CO_2 per year in Iceland. Current prices range from USD 600–1,000/t CO_2 captured and stored, with costs expected to go down to USD 150–200/t CO_2 within the next 10–15 years.

Figure 15: Direct air capture and storage process (stylized; supply chains not shown)



Key considerations

- **DAC is very energy intensive**, especially as compared to industrial CCS. CO_2 capture energy demand increases as the concentration of CO_2 decreases, and atmospheric CO_2 is very dilute, around 0.04% by volume, compared to 5–30% for industrial flue gas. Current DAC processes use 6–10 GJ/t CO_2 of energy to separate CO_2 from the atmosphere, compared to 3–5 GJ/t CO_2 for industrial CO_2 capture. Reducing the energy demand is the primary focus of most DAC technology companies.
- **DAC can be flexibly sited**, such as near available CO_2 transport and storage and/or low-carbon energy sources.
- To be a CDR technology, **DAC requires permanent storage**. If the removed CO_2 is reused in short-term processes, such as for fuels, chemicals, plastics, fertilisers, or greenhouses, it is not a removal, but a delayed emission.

Local drivers and barriers

The Porthos and Aramis pipelines to geologic storage (see BioCCS: Overview of sinks) could also be used to transport atmospheric CO_2 captured via direct air capture, and the modularity of many DAC designs facilitates siting DAC facilities near transport. Alternatively, DAC could be sited in urban areas, where it could contribute to reducing local air pollution, though this would increase the complexity of transporting the CO_2 to storage.

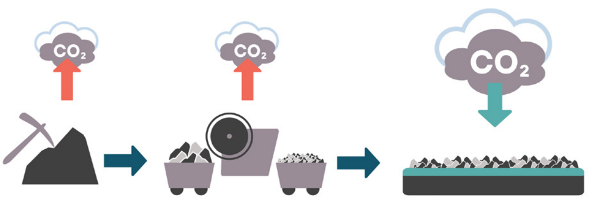
DAC would compete with local demand for energy resources, such as waste heat that could be used to facilitate industrial CO_2 capture. As the energy demand for DAC is currently 2-4x that of industrial CO_2 capture, **capturing industrial CO_2 is more energy efficient at reducing net emissions than DAC**. Furthermore, the average CO_2 intensity of the Dutch grid is 333 g CO_2eq/kWh (in 2020), which, if used to meet the energy demand of DAC, would emit 500–900 kg CO_2eq/tCO_2 removed. For DAC to be efficient in the Dutch context, the energy demand of DAC needs to be optimised and additional renewable energy is needed.

Direct air capture is a novel technology that requires substantial investment and 'learning by doing' to decrease energy demand and costs. Once CO_2 transport and storage infrastructure is available, **the NSCA could speed DAC development by funding the development of an 'off grid' DAC facility**, with independent renewable energy generation (e.g., wind, solar, geothermal) to prevent grid stress.

5.2 Enhanced weathering

Weathering is a normal geologic process by which certain rocks react with CO_2 and H2O in the atmosphere, which slowly dissolves the rock as it binds to the CO_2 and H2O. This dissolved rock (along with the CO_2) then ends up in the soil, as soil inorganic carbon, and eventually leaches into the ocean or underground aquifers. This process takes thousands to millions of years. Enhanced weathering is the attempt to accelerate this process by increasing the surface area of the minerals exposed to the atmosphere by grinding it into sand-sized particles (Figure 16). Silicate rocks such as olivine or basalt are most commonly proposed for enhanced weathering projects. One tonne of olivine can, at maximum, remove 1.25 tonnes of CO_2 from the atmosphere.

Figure 16: Enhanced weathering process (stylized; supply chains not shown)



Key considerations

- **Enhanced weathering is slow**, happening over years or decades. Gravel-sized olivine (3 mm) could lead to less than 5% CO_2 uptake (60 kg CO_2/t olivine) in the first 30 years, depending on site conditions
- **Smaller grind sizes increase weathering speeds**, but also increase energy use needed for grinding. Sand sized olivine (0.1mm) could have 80% CO_2 uptake (1 t CO_2/t olivine) in the first 30 years. Depending on site conditions.
- **Higher temperatures and higher moisture increase weathering speeds**. Weathering will occur faster if the olivine is exposed to rain, high humidity environments, or waves. Low temperatures, such as those found in temperate regions like the Netherlands, slow weathering reactions.
- **Health impacts of very fine olivine are unknown**. In particular, if very fine grinds (<0.01 mm) are used to speed CO_2 dissolution, the olivine would count as fine particulate matter (PM10), and thus a potential air pollutant.
- **Monitoring the fate of dissolved CO_2 is currently difficult**. In enhanced weathering, the CO_2 is not absorbed into the mineral, but rather dissolved into the soil below as inorganic carbon. While much of this CO_2 is assumed to remain stored, the final fate may be unverifiable.
- Silicates such as olivine or basalt **may affect soil chemistry if applied to agricultural soils**, such as reducing soil acidity, increasing mineral levels in the soil for both nutrient minerals (e.g. magnesium) and toxic minerals (e.g. nickel, chromium)

Local drivers and barriers

Enhanced weathering does not require dedicated space and can be applied to existing surfaces such as park pathways, sports terrain, traffic medians, agricultural soils, and rooftops. According to CNI, if all available traffic, sport, agrarian, recreation, forest terrain, and rooftops in the Amsterdam municipality were used, a maximum of approximately 1 Mt CO_2 could be removed from the atmosphere and would require approximately 800,000 t olivine. **The removals would occur over a period of years to decades, depending on grain size and local conditions**. After application, the minerals would be unlikely to require additional energy or labour inputs, except for monitoring and verification.

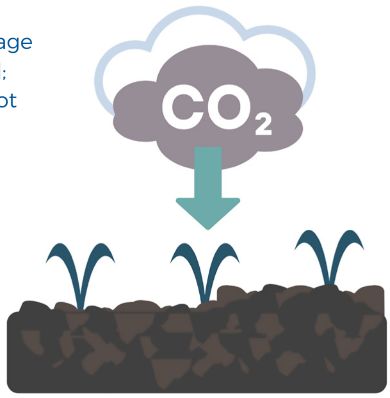
Application of olivine currently exists in a legal grey area, as it is not recognized as a construction material or fertiliser, and may be considered a 'foregin substance' that would limit potential use. Clarification of the legal status of enhanced weathering minerals is needed before large scale application could occur.

In the Netherlands, greenSand and Carbon Neutral Initiative (CNI) currently sell olivine for CO_2 removal purposes. In the interview conducted for this report, CNI has expressed interest in Amsterdam-region demonstrations projects. Given the uncertainties around removal rates and co-impacts, as well as the site-sensitive nature of enhanced weathering, real world implementation, such as **medium and large scale multi-year pilot projects, would be needed to assess how well enhanced weathering could work in North Sea Canal region**, including optimal grain size and siting options.

5.3 Soil carbon storage

Soil carbon storage (SCS) is the use of land management practices that increase the organic carbon content of soil (Figure 17). These practices include the increased application of carbon (e.g. manure, compost), and the decreased removal of carbon (e.g. erosion control, decreased tillage). The ability to increase soil carbon depends on the soil type; soil that has been already depleted (e.g., from extensive tillage) have a potential to restore lost carbon stocks, and thus result in CDR. For soils with high carbon content (e.g. peat soils), regenerative land management has the equally important benefit of preventing additional carbon loss—emission reduction rather than carbon removal.

Figure 17:
Soil carbon storage process (stylized; supply chains not shown)



Key considerations

- **Annual soil carbon increases are small** (<1 tonne per hectare per year) and the rate of increase decreases over time as the soil sink saturates.
- Soil carbon increases **can be difficult to monitor** and distinguish from natural carbon fluxes, as they can account for <1% of total soil carbon. This is particularly true for soils with existing high carbon content, like the peat soils that are common in the NSCA. Techniques for monitoring and models are described in existing methodologies, but project- and soil-specific baselines and monitoring techniques must be developed.
- Increasing soil carbon **has a higher associated risk of reversal and requires ongoing maintenance** to avoid losses of stored soil (e.g., via erosion).
- Land management practices that increase soil carbon **may have co-benefits, such as higher agricultural yields and water retention, improved water management and resistance to drought, reduced demand for chemical fertilisers, and soil biodiversity**.
- Increasing soil carbon may affect N2O emissions, due to the link between the soil carbon and nitrogen cycles.

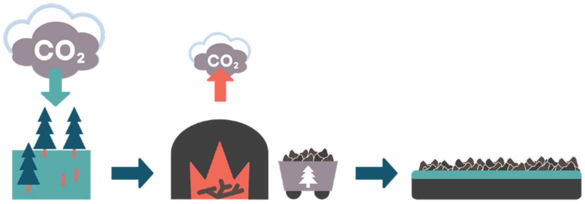
Local drivers and barriers

In the Netherlands, the average hectare of soil contains between 52 and 191 tonnes of carbon per hectare in the top 30 cm, with 123 tonnes/ha for grassland, including grazing land – dairy and meat farms make up 95% of the farms in the Amsterdam region. There are 35,252 ha of agricultural land in the Groot-Amsterdam COROP statistical area, of which 2,638 are in the municipality of Amsterdam itself. At a rate of increase of ~1 tonne/ha/year (the average range of increase in European projects is 0.5–1.5 tonne/ha/year, depending on specific activities), agricultural soils could store over 35,000 t CO_2/year. However, the average farm size is small, around 50–60 ha according to Wij.land. They assess that the combination of small farm size and slow rate of increase means that **'results-based' compensation of CDR credits would be unlikely to compensate for the difficulty of verifying increases and the administrative burden. Instead, practice-based compensation that supports long-term regenerative practices would allow for increases in soil carbon as a co-benefit**, rather than a targeted outcome. Wij.land has expressed willingness to be an intermediary between the municipality and regional farmers to work together to promote regenerative practices.

5.4 Biochar

Biochar is woody biomass that is pyrolysed into a charcoal-like substance, after which it can be pulverised and applied to soil or simply buried (Figure 18). While predominantly applied in soils, recent innovation allows permanent storage of biochar carbon in other materials, such as concrete or asphalt. Biochar is porous hydrophobic and can be used to increase water retention in soils. Depending on the type of biomass and pyrolysis conditions used, biochar carbon can be very stable, with potentially 80+% of stored carbon remaining in the soil for hundreds of years.

Figure 18: Biochar process (stylized; supply chains not shown)



Pyrolysis

Pyrolysis is combustion in the absence of oxygen and produces a mix of gases, oil, and solids (biochar). Pyrolysis gas can be combusted for energy or used to produce synthetic fuels. Pyrolysis oil can also be used as a fuel source but has a short shelf-life due to a high oxygen content. Pyrolysis oil can also be reinjected back into geologic reservoirs as a form of CDR.

Key considerations

- **Not all biochar is equal**. The type of biomass used and the pyrolysis conditions both impact the properties and stability of the biochar. Biochar can be between 70–90% carbon, roughly translating to 2.5–3.0 tonnes of CO_2eq stored in each tonne of biochar.
- **CDR removal potential depends on the sustainability of the source biomass supply chain**. Besides the cultivation and transport of biomass, the pyrolysis process needs to be carefully controlled to prevent methane emissions.
- The dark colour of **biochar decreases albedo**. While this effect is not thought to be significant and is generally not included in carbon accounting methodologies, it may increase local warming and soil temperatures. This warming impact needs to be assessed in the context of already increasing heat stress, both in areas where the biochar is applied and areas affected by wind-lost biochar (Bond et al 2013).
- **Overall impact on agricultural soils and yields is highly situational**. If used as a soil amendment, changes to crop productivity, water retention, and nutrient demand may occur due to changes in soil structure, soil carbon balance, microbiome, and albedo. The impact of biochar is dependent not only on the type of biochar, but also the application rate, soil type, and climate. When used correctly in soil, biochar is understood to have co-benefits in soils, such as increased water retention, increased and delayed nutrient distribution, and improved soil properties.

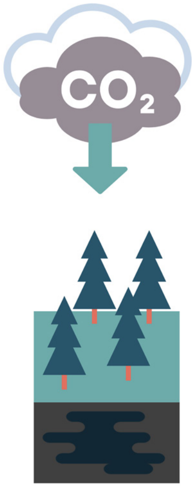
Local drivers and barriers

Multiple Dutch producers of biochar market biochar as a soil amendment and CDR technology, including PyroPower, First Tree, and Greenwave Biochar. Biochar is produced in Amsterdam as a byproduct of the biosyngas production of Bio Energy Netherlands, at a rate of 1,000 t biochar/year. However, currently that biochar is classified as a waste, with the end-of-waste regulation as the primary hurdle for reuse of biochar. Their biochar is landfilled, which does result in similar storage as application to soils, but provides no compensation or incentive for the carbon storage. Besides carbon storage, biochar's use as a soil amendment to prevent water loss could support adaptation to ongoing climate change. However, large-scale pilot studies are needed to understand the overall impact of specific biochars on Dutch soils. Furthermore, **Cargill**, which produces biochar, expressed concerns at the small market for biochar as a soil amendment in the EU compared to regions such as Africa, especially considering the small scale of their production (~8,000–9,000 t per year).

5.5 Afforestation

Afforestation is the storage of atmospheric carbon in the living biomass of deliberately planted and maintained long-lived biomass, such as trees (Figure 19). Afforestation has many non-CDR purposes, such as restoring biodiversity, maintaining soil fertility, increasing wood supply, aesthetic improvement, and local economic prospects.

Figure 19:
Afforestation process (stylized; supply chains not shown)



Key considerations

- Carbon storage in living biomass is not inherently permanent and **requires careful and continuous management**.
- Afforestation has a **high risk of reversibility**, from fire, pests, disease, and mismanagement. Plans for afforestation must include procedures and financing for monitoring as well as replacing lost trees.
- **Newly planted trees grow slowly**, with fastest CO_2 uptake in the tree's midlife, and finally slowing to saturation as the tree matures, though rates vary widely between tree species.
- **Careful species selection is needed to avoid ecosystem stress**. Tree selection should take into account local considerations such as available water supply and soil nutrients, including expected future changes due to climate change.

Local drivers and barriers

The Amsterdam municipality has approximately 1 million trees, with a goal to plant an additional 8,000–10,000 trees over 2020–2023, and has provided subsidies for small-scale urban tree planting initiatives. Trees can reduce the heat island effect and erosion, as well as improving biodiversity and increasing the attractiveness of urban and natural areas. However, as reported by Wij.land, r**estrictive land use regulations currently make it difficult to plant additional trees on agricultural lands**. Besides direct planting initiatives, reducing the administrative burden, as well as providing assistance with species selection and maintenance, can help increase local afforestation. However, **the impermanent nature of biologic sinks means that using afforestation for creditable CDR would require deliberate planning to manage risk of reversal**.

5.6 Standalone CDR options summary

Several CDR options exist that can be implemented independently of industrial activity, including:

Direct air capture with geologic CO_2 storage (Carbyon): using energy and chemicals to extract CO_2 out of the air and store it underground.

- Scalable
- Flexibly Sitable

- Currently very energy intensive
- Requires access to geologic storage

Key challenge: Resource intensive → Competition for limited resources (e.g., energy, water, CO_2 storage capacity)

Enhanced weathering (Carbon Neutral Initiative): spreading ground minerals that dissolve atmospheric CO_2 into the soil over a period of years/decades.

- Dedicated land not required
- Flexibly sitable

- Very slow
- Low potential per hectare

Key challenge: Carbon dissolves into soil → Monitoring and verification

Soil carbon storage (Wij.land): increasing organic carbon stocks via application of composts and such and the prevention of erosion

- Part of good agricultural land management

- Risk of reversal
- Low potential per hectare

Key challenge: Carbon increases are small compared to existing carbon stocks → Monitoring and verification

Biochar (Bio Energy Netherlands): producing charcoal that is then stored in soils or underground

- Scalable
- Can improve water retention

- High biomass demand
- High variability of quality and net emission

Key challenge: Mix of stable and unstable carbon distributed in soils → Monitoring and verification

Afforestation: increasing – and indefinitely maintaining – long-term biomass stocks

- Many co-benefits
- Typically popular

- Subject to sink saturation
- Requires large amounts of land

Key challenge: Biomass sensitive to environmental hazards → Risk of reversal

While all of these CDR options have some potential for implementation in the NSCA, none are a panacea, or a replacement for rapid emission reduction. Pilot studies to understand regional-specific potential and how to best verify and monitor different types of CDR are key near-term actions, along with easing hindering regulation, such as land use restrictions for afforestation and the 'foreign substances' status of biochar and enhanced weathering minerals.

6. Conclusion and recommendations

6.1 Key takeaways

→ **There is no net zero without CDR – CDR should be an integral part of a municipal and regional climate strategy.**

- However, the development and deployment of CDR must not deter from deep emission reductions. The focus of any climate strategy should be on: i) preventing additional emissions from being released; and ii) reducing existing emissions, thus minimising what must be compensated with removals.
- While bioCCS provides carbon removal, it should not overshadow conventional fossil CCS, which lead to emission reductions. The promotion of bioCCS should be part of a wider deployment of carbon capture with permanent storage for any fossil emissions.
- The availability of CDR to balance municipal emissions will be limited within the urban environment itself. Appropriate storage opportunities are likely to be located outside the Amsterdam metropolitan area and the NSCA.

→ **Individual CDR solutions each have their own merits and limitations, and should not be considered equivalent.**

- CDR activities must be rooted in the fundamental scientific principles of physical, permanent, and net removal of CO_2 from the atmosphere.
- CDR activities must be selected based on local context and specificities.
- Co-benefits of CDR options should be measured – and incentivised – separately.
- CDR claims must only be made for removals that have already occured, not that will occur in the future. This is particularly relevant for slow-acting CDR options such as enhanced weathering and afforestation.
- Land-management-based CDR, such as soil carbon storage and afforestation, could be quick to implement and have a high potential for co-benefits, but also has low total potential due to land-dependence, may be difficult to monitor, and will require continuous management to balance a high risk of reversal.

→ **While there is potential for CDR in Amsterdam and the NCSA, the development and deployment of these processes are hindered by a number of factors, as addressed in this report.**

- Limited data is available on regional biogenic CO_2 emissions preventing a complete overview of the full potential.
- There is a lack of stable demand for removals and financial incentives to establish CO_2 capture for biogenic CO_2 emissions and to store that CO_2, rather than sell it for reuse (e.g., to greenhouses).
- High uncertainties remain concerning the mitigation and financial viability potential of standalone CDR options, particularly in the NCSA regional context.
- Cumbersome regulation and permitting processes – and regulatory ambiguity – are a hurdle for bioCCS ('end-of-waste' regulation), afforestation (land use limitations), and biochar and enhanced weathering ('foreign substance' status).
- CDR will compete with other demand for captured CO_2. The lack of financial valuation of CDR leads to CCU activities, such as for the large greenhouse facilities in the Netherlands being the intended destination of current plans for captured biogenic CO_2.

6.2 Key takeaways

→ **Set a CDR-specific target and roadmap.**

- Setting a CDR-specific target can be the turning point to signal to industrial stakeholders and decision makers, even in the absence of legal enforcement mechanisms at municipal level.
- Such a target should include volumes per year and a specified timeline, to enable a more focused approach, while embedding it in the city and NSCA's broader climate strategy as a complement to emissions reduction targets.
- A CDR roadmap should identify the CDR mix (various selected CDR options) that enables the achievement of the target. This will enable the development of solutions conducive to achieving the target, including financial support.

→ **Dedicate more resources to research for, development and accounting of CDR.**

- More comprehensive studies are needed to define the CDR potential at the municipal and regional scales, by 2030, 2050 and beyond.
- Reporting requirements for biogenic emissions need to be put in place to remedy current data gaps.
- Biomass is not inherently sustainable. While the sustainability of the upstream supply chains of biomass wastes is conventionally not considered, biomass in general should not be considered "carbon neutral". In particular, the use of dedicated biomass, now or in the future, requires critical evaluation of its origin and supply chain sustainability to determine the net-removal potential of bioCCS.
- Pilot studies of stand-alone CDR options such as enhanced weathering, soil carbon storage, and biochar are needed to provide region-specific knowledge on co-impacts and implementation optimization.
- Quantification of CDR potentials must account for the variance both in the speed of CO_2 removal and the performance of CO_2 storage.

→ **Take a more active role in supporting CDR activities at the municipal and regional scales**.

- The most requested assistance from the interviewed stakeholders was help from local authorities in streamlining hindering permitting processes, particularly the 'end of waste' criteria. Other hindering regulations identified include land use restrictions on multi-use spaces (e.g., 'nature' vs 'agricultural' land), and the status of spreading 'foreign materials' (e.g. biochar, olivine) on soils and other lands.
- The municipality and region must be clear on its standards to ensure CDR credibility as well as the required monitoring, verification, and maintenance of sinks.
- The municipality and region can help design funding pathways for CDR options, such as: i) via their procurement strategies, to require any emissions that cannot be reduced be offset with credible and permanent removals, or require, e.g. the use of mineralised or recycled concrete; and ii) valuing public goods such as urban greenspaces and agricultural carbon sinks that are funded through, e.g. property taxation.
- The municipality and region should take a central role in convening stakeholders and resources, e.g. to facilitate the creation of CDR and CCS innovation hubs.
- The municipality and region are also well-placed to raise awareness and undertake educational activities to raise the social legitimacy of and commercial interest in CDR.
- The municipality and region should promote CDR activities at the national level, for example by lobbying the national government for legislation and regulatory incentives to deploy CDR at scale.
- The municipality and region can promote harmonised regional assessments of CDR demand and potential to help assess the potential supply versus anticipated demand to better inform realistic climate action plans. CDR use must be assessed in the context of competing demand for limited resources such as CO_2, land, biomass, and energy.

6.3 Call to action

Cities are a critical arena for climate action. Urban areas will account for over half of global increase in carbon emissions by 2030. They concentrate economic, political and cultural activity, and are motors of change and innovation, able to transform human structures, and design, facilitate and implement concrete actions. Cities are a critical actor in the multi-level governance of climate politics, at times acting independently from their national government. The city is therefore an important scale for climate and removals action, particularly when considering the ubiquitous and inclusive approaches needed to deploy CDR. Although a large number of cities have committed to net zero, they may not have the knowledge, capacity or network to integrate removals in their strategies or implement city-scale removal solutions. It is crucial that the municipality of Amsterdam and the NSCA deepen their knowledge, build their capacity and expand their network to reach their climate goals.

The municipality of Amsterdam is already at the forefront of climate change action, having committed to ambitious climate goals and taking part in initiatives such as the EU Mission for Climate-Neutral and Smart Cities. It is also taking steps to develop its understanding of the potential for emissions reductions and removals, through this study and a similar quick scan conducted on CCU potential. Its proximity to biogenic emission sources in surrounding industrial areas and potentially massive storage potential in the North Sea makes it a prime candidate to explore CDR at a large scale. By being an early adopter and promoter of CDR, the region also stands to become a hub for CDR solutions and industry, attracting businesses and stimulating a sector increasingly recognised as essential to mitigating climate change.

The municipality of Amsterdam and NSCA should contribute to driving the acceleration toward the deployment of CDR, thereby catalysing private sector action, rather than the opposite. CDR, as essential to reach climate goals, must be considered a public good, rather than a purely commercial or industrial undertaking. In the same way that local governments provide waste management services (e.g. for sewage and water), the provision of – or promotion of – CO_2 management services could be foreseen to be an essential public service.

Immediate next steps for the City of Amsterdam and the NSCA:

→ Address the end-of-waste regulation, which must be streamlined to facilitate the capture of both biogenic and non-biogenic CO_2.

→ Comprehensively identify and quantify the opportunities for the capture, transport and storage of biogenic emissions, and for the use of standalone CDR solutions.

→ Explicitly address the role of CDR envisaged in municipal and regional climate strategies.

→ Set a CDR-specific target to catalyse investment in and development of CDR activities.

→ Take an active role in innovation, e.g. by showcasing demonstrations and pilots.

→ Convene a multi-stakeholder group to inform a CDR deployment roadmap.

→ Advocate with other Dutch and international cities for national CDR policies and funding.

→ Convene a citizen assembly on removals to start building social legitimacy.

7. Annexes

7.1 Methodology

7.1.1 Data collection protocol

The collected data was informed by the following.

- A review of existing data to form the basis of the data collection needed to conduct the analysis. The municipality shared some existing data on biogenic emissions of companies, but this was found to be very restricted.
- Information from the NSCA Environmental Service on additional biogenic emission sources;
- Information from &Flux, during the implementation of a similar CCU quick scan;
- Interviews with companies in the geographical area covered by the project;
- Interviews with companies specialising in standalone CDR activities, which were not all Amsterdam-specific;
- Interviews with companies outside the geographical area covered by the project, when these were deemed sufficiently relevant to the project;
- Existing literature – e.g. on costs and emissions of removal, transport and storage options – to inform the assessment of negative emission potential.

An initial list of companies to interview was developed based on: i) South Pole market expertise; ii) Bellona Europa expertise; and iii) suggestions from the Municipality of Amsterdam. From an initial list of ~40 entities, 16 interviews were conducted in the scope of this project (Table 5). Final interviewees were selected based on perceived relevance and responsiveness of stakeholders. While this is not an exhaustive list of all the biogenic CO_2 emitters, transport providers and storage providers in the project geographical scope, they provide an indicative representation of types of CDR-relevant stakeholders.

Table 5: Interviews conducted

Type	Name of entity	Description
Sources of biogenic emissions	**AEB**	Waste-to-energy
	Cargill	Agricultural products
	Future Biogas	Biomethane
	Gidara Energy	Biomethanol
	Waternet	Wastewater treatment
Transport for and sinks of biogenic emissions	**Porthos**	Carbon transport and storage
	Mitsubishi Corporation	Carbon mineralisation in building products
	SIKA	Carbon mineralisation in building products
	OCAP	Carbon transport
	Air Liquide	Carbon processing and transport
Standalone CDR solutions	**Bio Energy Netherlands**	Biochar (in future: hydrogen production)
	Carbyon	Direct air capture
	Carbon Neutral Initiative	Enhanced weathering
	Wij.land	Carbon farming
Others	**TNO**	Research (carbon transport and storage)
	Omgevingsdienst NCSA	Regional environmental service entity

7.1.2 Assessment criteria

The following assessment criteria was developed to compare and assess the data collected during the data collection stage described above (Table 6). After a section applicable for all interviewees, the assessment is separated into sections for biogenic carbon emitters, off-takers, and for standalone CDR options.

Table 5: Assessment criteria

Criteria	Unit	Description
All components		
Description	n/a	Description of the specific process, technology or solution
Technology readiness level (TRL) of solution	Integer	9: Widespread commercial operation, 8: First-of-a-kind full scale commercial operation, 7: Pre-commercial demonstration scale, 6: Pilot scale, 5: small-scale pilot. (Projects with research-level only TRLs not considered)
[Proposed] Start of operations	Year	Year of (expected) start of operations
Current stage of project development	n/a	Extant, planning for full-scale operation, test scale operation, test scale planning, exploration, no plan
Location	n/a	Geographic location
Scale (present)	kt CO_2/yr	Scale of biogenic carbon emissions OR scale of storage capacity OR scale of removals achieved
Scale (expected by 2030)	kt CO_2/yr	As above, expected by 2030
Estimated electricity demand	kWh/t CO_2	Electricity consumption – may be based on generic data
Estimated thermal energy demand	GJ/t CO_2	Heat consumption – may be based on generic data
Estimated emissions	t CO_2e/tCO_2	Ballpark estimate of greenhouse gas emissions associated with activity – may be based on generic data
Cost Estimation	EUR	OPEX (per tCO_2) and CAPEX (total) for activity
For CO_2 sources		
Point source % of CO_2	%	Concentration of CO_2 in flue gas stream
Other flue gas considerations	n/a	E.g. composition of gas, risks of contamination
Biogenic/atmosphere fraction of CO_2	%	Percentage of CO_2 that is of atmospheric origin (non-fossil)
Carbon source	n/a	Origin of carbon (waste, crops, wood…)
Available waste heat	GJ/year	Unused heat that could be used for CO_2 capture heat demand
Available space	n/a	If the space is available for the CO_2 capture equipment
Available CO_2 transport options	n/a	Based on the location of the source site
Envisaged offtakers	n/a	Identified off-takers of the biogenic carbon
For CO_2 sinks		
Durability of storage	Years	Timescale of carbon storage in selected sink, may be based on generic data
Storage medium	n/a	Where the CO_2 is physically stored
MRV-viability	low/med/high	How easy it is to monitor the continuance of CO_2 storage. May be based on generic data
Risk of reversibility	low/med/high	Likelihood of the CO_2 is likely to be re-released into the atmosphere. May be based on generic data
[Expected] CO_2 sources	n/a	Where the stored CO_2 is already expected to come from
Available transport options	n/a	How the CO_2 arrives at the storage site
CO_2 quality requirements	n.a.	Requirements such as purity, pressure, maximum level of contamination…
For stand-alone CO_2 removal options		
Removal mechanism	n/a	How CO_2 is removed from the atmosphere
Storage medium	n/a	Where the CO_2 is physically stored
Carbon source	n/a	Origin of carbon (atmospheric, waste, crops, wood…)
MRV-viability	low/med/high	Ease of monitoring the continuance of CO_2 storage. May be based on generic data

Criteria	Unit	Description
Risk of reversibility	low/med/high	Likelihood of the CO_2 is likely to be re-released into the atmosphere. May be based on generic data
Durability of storage	years	Timescale of carbon storage in selected sink, may be based on generic data
Removal efficiency	%	Amount of CO_2 removed compared to estimated GHG emissions
Available transport options	n/a	How the CO_2 is transported (if relevant)
Expected payback period	Years	Time before the CO_2 removal technology stores more CO_2 than the process emitted. May be based on generic data

7.2 Guiding questions for interviews

The following text and lists of questions were developed to guide the interview process to gather further data from identified companies. While these are intended to cover a wide range of topics, informed by the assessment criteria, it should be noted that they are 'guiding' only and that interviews may have covered additional or more specific subtopics. These questions were adapted for interviews with CO_2 transport providers and standalone CDR companies.

Introductory text:

As part of a project commissioned by the Amsterdam municipality to assess the negative emissions potential in the region, we are conducting a survey of potential suppliers of biogenic and atmospheric CO_2. We would like to understand what potential CO_2 streams are available, if you have any existing plans for emission reduction, and your general thoughts on CO_2 capture and related technologies.

Aside from the quick-scan, a) this is an exploration of decentralised urban CDR potential more generally, and b) this will likely feed into an in-depth study by the Amsterdam municipality.

7.2.1 Questionnaire for CO_2 sources

- What existing gas streams produced at your facility contain biogenic/atmospheric CO_2?
- What is the carbon source? (e.g., type of biomass)
- What is the volume and composition of these gas streams?
- If the gas stream contains a mix of biogenic and fossil CO_2, what fraction is biogenic and what fraction is fossil?
- Is there any existing CO_2 capture or plans for CO_2 capture in the future? If so, what type of capture and on what timeline?
- If any (planned) CO_2 capture exists, what is the (proposed) fate of the CO_2?
- If CO_2 capture was installed, is there waste heat or other energy already available?
- Is there space available at the facility for a CO_2 capture installation?
- For possible CO_2 transport, does the facility have access to
    - space for a pipeline?
    - rail access?
    - canal/harbour access?
- Are there non-CO_2 capture based plans to reduce the CO_2 emissions of the facility? If so, on what timeline?
- Do you have any thoughts on main barriers for CO_2 capture at your facility?
- Do you have any thoughts on what would be required to incentivise CO_2 capture at your facility?
- Are you familiar with the concept of 'carbon dioxide removal' (aka 'negative emissions'), and do you have any opinions on how they relate to your operations? Or in general?

7.2.2 Questionnaire for CO_2 sinks

- What is the storage location?
- What is the storage medium?
- What transport options are there to transport CO_2 from source to sink?
- What sources of CO_2 are typically used?
- What processes are used for sequestration?
- When is/were the start of operation (if relevant)?
- What are conservative estimates of CO_2 storage in tonnes per year (now and projected in the future)?

- What is the estimated durability/ timescale of storage?
- What is the TRL of the storage solution?
- Is the process MRV viable?
- What is the cost (per tonne if possible)?
- Ownership of carbon rights?
- Certification?
- What would be required to incentivise CO_2 storage?
- What are drivers and barriers to CO_2 storage?
- What are the co-benefits of the storage solution?

7.3 Comparative analysis

Please refer to the attached comparative analysis table.

south pole

BELLONA
EUROPA