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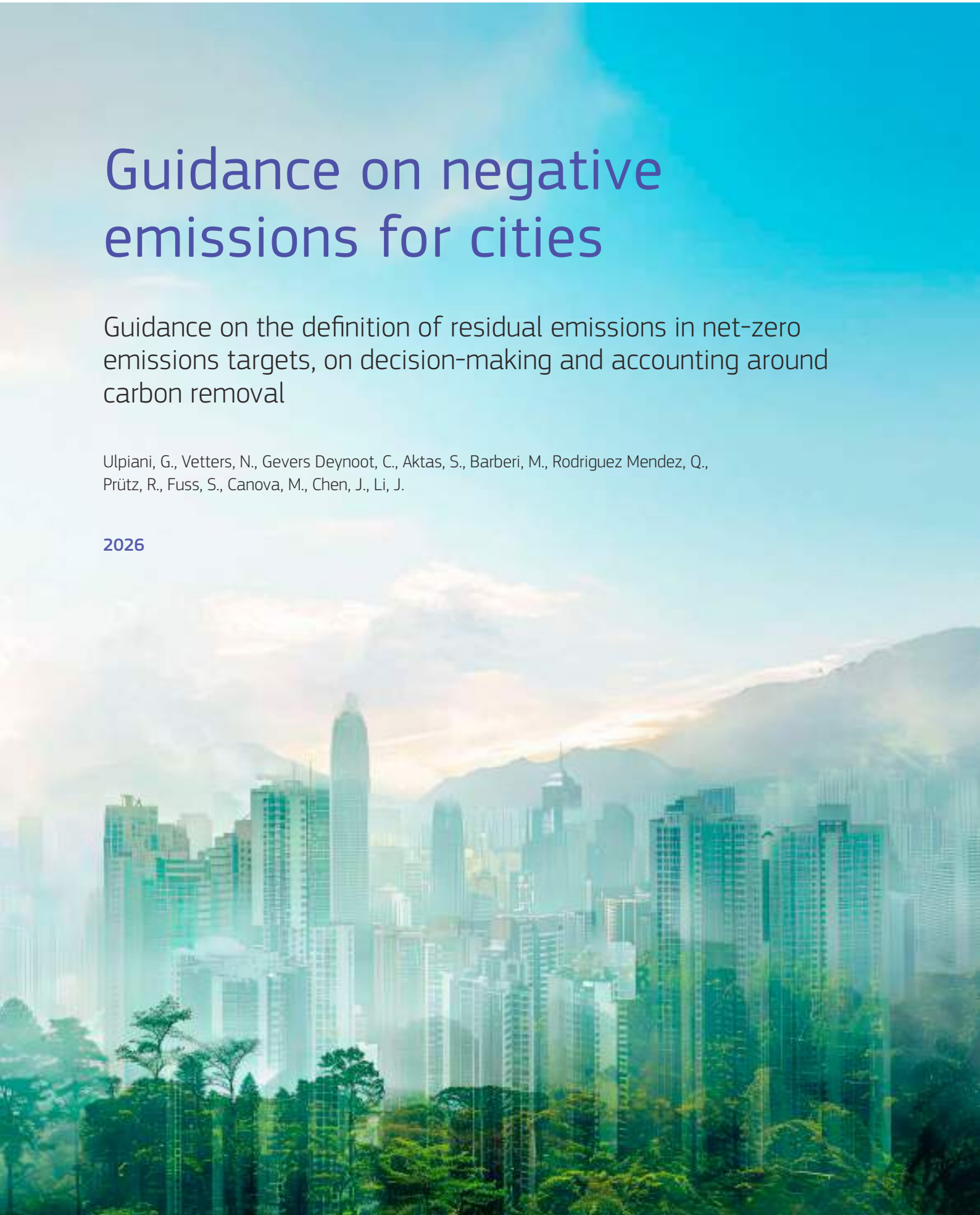
Joint Research Centre

# Guidance on negative emissions for cities

## Guidance on the definition of residual emissions in net-zero emissions targets, on decision-making and accounting around carbon removal

Ulpiani, G., Vetters, N., Gevers Deynoot, C., Aktas, S., Barberi, M., Rodriguez Mendez, Q., Prütz, R., Fuss, S., Canova, M., Chen, J., Li, J.

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## Abstract

This “Guidance on negative emissions for cities” primarily addresses cities involved in the 100 Climate-Neutral and Smart Cities Mission but can be used as a conceptual and practical reference by any city targeting net-zero emissions. The main objectives are to offer precise directions for negative emissions strategies and accounting, distil key principles and create a conceptual framework around the use of emissions compensation mechanisms (local carbon removals and carbon credits). The focus is on guaranteeing high climate and environmental integrity, managed through a transparent and ethical process, aligned with international best practices. Key recommendations include ensuring clarity in target boundary definitions, reporting separately each term of the net emissions equation (gross emissions, in-boundary removals, sold and retired credits), and avoiding double counting or claiming. This guidance underscores the importance of delivering a compelling set of co-benefits and diversifying compensation strategies while providing practical advice for cities to develop time- and cost-effective residual emissions strategies. It does not shift the attention away from the key objective of a climate neutrality target: priority is always on emissions reduction at source. A “Summary for Decision Makers” is published alongside this guidance to provide a concise and actionable roadmap for decision-making, referencing back to this document for deeper analysis and further reading.

## Acknowledgements

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## Executive summary

This guidance aims to clarify how compensation mechanisms that sequester atmospheric emissions through anthropogenic activities can be transparently and legitimately used to achieve urban climate neutrality. It provides conceptual frameworks, practical guidance, and recommendations for decision-making.

### *Policy context*

The European Union, through the Paris Agreement and the European Green Deal, has set ambitious targets for reducing greenhouse gas emissions. The 100 Climate-Neutral and Smart Cities Mission is part of these efforts, supporting selected cities in achieving absolute- or net-zero emissions by 2030. The report aligns with EU legislation, such as the EU Climate Law and the Carbon Removal and Carbon Farming Regulation and connects with various EU initiatives promoting climate change mitigation, environmental resilience, and a circular economy.

### *Key conclusions*

This guidance emphasises the importance of defining residual emissions analytically, rather than through target-setting, to strengthen accountability and prevent over-reliance on carbon removals. This approach can help prevent delays in fossil fuel phase-out or inflation of long-term costs. The guidance stresses the importance of transparency, environmental and ethical integrity, and co-benefits in designing a robust residual emissions strategy. To achieve net-zero emissions, cities shall compensate for residual emissions through in-boundary atmospheric removals or high-quality carbon credits tied to verified removal activities under frameworks such as the EU Carbon Removal and Carbon Farming Regulation. Permanent methods (e.g., engineered storage) generally offer higher integrity than impermanent nature-based options. However, mixed portfolios that combine different approaches can improve co-benefits, reduce risks and hedge against market volatility. Cities can leverage both land and building carbon stocks, play different roles (e.g., regulator, investor, convenor, innovator), and explore cooperative procurement and alliances to scale impact. Transparent accounting consistent with IPCC principles is essential: emissions, removals, sold credits and retired credits shall be reported separately to prevent double counting and ensure public trust. Robust monitoring, reporting, and verification systems shall be in place over the full lifetime of each project. Ethical and environmental safeguards and equitable risks and benefits distribution should be integral components of the residual emissions strategy, as poorly designed removals can harm ecosystems or communities.

### *Main findings*

— In net-zero targets, compensation is mandatory for residual emissions, but cities are urged to prioritise the reduction of emissions at their source over compensation mechanisms whenever possible. While carbon removals may be part of a broader urban agenda, their use in reaching net-zero emissions should be limited to when technically and economically feasible emissions reduction options have been exhausted.

— Cities can leverage in-boundary carbon removals and/or out-of-boundary carbon removal credits (verified) to compensate for their residual emissions. Valid removals shall originate from deliberate activities extracting atmospheric GHGs and storing them durably. Fossil-source capture lowers emissions but does not count as removal. Reduction or avoidance credits cannot offset residuals and credits sold externally cannot count toward a city's own balance.

— Compensation options should be chosen based on their environmental and ethical integrity and their potential to generate co-benefits. They should be combined in a portfolio of options that emphasises diversification as well as time- and cost-effectiveness. Cities shall consider the timing of their strategies to ensure alignment with the 2030 (or other) timeline.

— Negative emissions necessitate a clear and transparent monitoring and accounting framework to ensure credible and verifiable climate neutrality targets. Guidelines are provided for cities to accurately report positive and negative emissions as well as carbon credits, following established principles and methodologies as concerns data sourcing, calculation, and uncertainty management (notably for the land sector and the built environment).

***Related and future JRC work***

This guidance supports the 100 Climate-Neutral and Smart Cities Mission and other EU flagship initiatives on urban climate action (e.g., Covenant of Mayors) to achieve the long-term objectives of the Paris Agreement. The JRC will continue to explore and share best practices for net-zero targets.

***Quick guide***

This document outlines how to:

— Apply an analytical approach to identify residual emissions in urban net-zero targets.

— Select high-integrity emissions compensation options, based on local characteristics and availability, considering co-benefits and trade-offs, timelines, and investment options.

— Diversify strategies to distribute risks and benefits.

— Report emissions transparently and avoid double counting.

Engage in JRC work and knowledge exchange to stay updated on best practices and emerging methodologies.

# 1 Introduction

The transition to a climate-neutral society is both an urgent challenge and an opportunity to build a better and safer future for all.

With the Paris Agreement, adopted in 2015, 195 countries – including the European Union and its Member States - committed to taking action to hold the increase in global average temperature compared to pre-industrial levels well below 2°C, and to making efforts to limit the temperature increase to 1.5 °C. To this end, the contracting parties agreed to reach net-zero greenhouse gas (GHG) emissions in the second half of the 21st century at the latest by balancing GHG emissions with removals resulting from human activities. Accordingly, both emission reductions and anthropogenic removals are behind the arithmetic of net-zero emissions.

In 2019, the European Green Deal set out a comprehensive roadmap for making the economy sustainable and climate-neutral (i.e., net-zero GHG emissions) by 2050. In July 2021, the European Union adopted the European Climate Law. In addition to the goal of climate neutrality and an aspirational goal for the Union to strive to achieve negative emissions after 2050, the European Climate Law sets a binding Union climate target of a reduction of net GHG emissions by at least 55% by 2030 compared to 1990 levels.

Three parallel processes need to occur at scale in order to deliver on these climate targets. First, efforts should be intensified to improve the efficiency of buildings, transport modes and industries, to move to a circular economy, and to massively scale up renewable energy. Second, carbon recycling from waste streams, sustainable sources of biomass or directly from the atmosphere, should be leveraged to replace fossil carbon in the sectors of the economy that will inevitably remain carbon-dependent (e.g., agriculture, heavy industry, aviation). Third, increasing amounts of carbon dioxide ($CO_2$) will have to be captured and removed each year from the atmosphere to compensate for hard-to-abate emissions from sectors like agriculture, cement, steel, aviation or maritime transport in view of reaching climate neutrality (European Commission, 2024). This is essential to halting global warming, stabilising the climate and curbing the most severe impacts of climate change. This three-pronged approach is in line with the IPCC Special Report on Global Warming of 1.5 °C (IPCC, 2018b) which maps four pathways consistent with limiting the temperature rise to 1.5 °C based on different assumptions and mitigation approaches. The analysis reveals that meeting the goal would require intensified emissions reduction efforts, as well as introducing compensation mechanisms for those emissions that cannot be reduced or avoided. This is confirmed in the latest IPCC Assessment Report that clearly states that “the deployment of carbon dioxide removal to counterbalance hard-to-abate residual emissions is unavoidable if net-zero $CO_2$ or GHG emissions are to be achieved” (IPCC Working Group III, 2022b). However, the EU is not on track: carbon removals in natural ecosystems have been decreasing in recent years (a trend worsened by climate impacts such as wildfires, droughts and floods) (Korosuo et al., 2023), and no significant industrial carbon removals are currently taking place in the Union (European Parliament and Council, 2024b). The EU's declining carbon sink, combined with the slow development of new carbon removal technologies, highlights the pressing need for robust policy action at all levels to effectively compensate for residual emissions from sectors where emission reductions are currently not feasible or options are too limited to serve the needs of all. Moreover, this evidence calls for intensified efforts and guidance provision in the deployment, reporting, and tracking of sustainable activities for capturing $CO_2$ from the atmosphere and durably storing it in geological reservoirs, terrestrial and marine ecosystems, or products, while ensuring a robust and transparent emissions accounting process. The European Union has established a comprehensive framework of policies,

directives, regulations, and communications aligned with this objective (European Scientific Advisory Board on Climate Change, 2025). Ongoing efforts focus on innovation, regulation, and funding to accelerate the development and implementation of carbon removal frameworks and technologies across various sectors of the economy, treasuring transparency, and promoting a co-benefits approach (see **Section 9**).

Actions taken by local communities will be key. It is increasingly clear that delivering on the European Green Deal would not be achievable without cities in the vanguard of concerted efforts. Cities are uniquely positioned to drive the systemic change required to limit climate change as they sit at the intersection of people and places, being close to the needs of citizens, businesses, and ecosystems. Acting swiftly and decisively against climate change is imperative for cities, as the price of inaction escalates with each delay in taking measures, severely affecting both citizens and urban functions.

Well-grounded in this vision and deeply rooted in research & innovation, the 100 Climate-Neutral and Smart Cities Mission (hereinafter, Cities Mission) is showcasing the European Green Deal at the local level and is supporting cities in navigating the unprecedented challenge of bringing local emissions to zero in a very limited timeframe. The 112 selected cities (hereinafter, Mission Cities) are to deliver net- or absolute-zero emissions by 2030, through bold actions and policy/regulations revamping, green and digital transitions, citizen engagement, circular models, governance and social innovation. Upholding such an ambition calls for a concerted and well-structured approach to emissions eradication, where abatement efforts are brought to their feasibility limit, and residual emissions (if any) are duly compensated.

Methodological frameworks and legal provisions related to carbon removal are becoming more accessible in Europe and beyond, often directed at the national level, without adequately addressing the contribution of cities. Against this backdrop, this guidance explores when, what and how emissions compensation mechanisms should be deployed and accounted for by cities on a net-zero emissions journey. It capitalises on the principles of the EU Carbon Removal and Carbon Farming (CRCF) Regulation (European Parliament and Council, 2024b) and explores how they can be meaningfully interpreted and applied at city level. Guiding principles are set out to inform decision-making and to support the design of robust monitoring, reporting, and verification (MRV) processes. The emphasis is on quality, traceability, and permanence criteria for carbon removals.

# 2 Aims and uses of this guidance

According to the IPCC Special Report on Global Warming of 1.5 °C and the 6th Assessment Report (IPCC, 2018b; IPCC Working Group III, 2022b), the expression "negative emissions" refers to the "removal of greenhouse gases from the atmosphere by deliberate human activities, i.e., in addition to the removal that would occur via natural carbon cycle processes". This guidance seeks to shed light on how negative emissions resulting from compensation mechanisms (local removal or purchase of verified carbon removal credits) should be accounted for in the realisation of urban climate neutrality with the following main goals:

- Define a conceptual framework around "residual emissions" to establish a shared understanding of which emissions should be compensated for in net-zero targets and how cities can transparently identify them (see in particular **Sections 3, 4, and 6.1**).
- Provide practical guidance and scientific support in planning for the compensation of residual emissions by elucidating principles (**Section 6**), options (see in particular **Sections 5, 7.1, 7.2** and the **Annexes**), and best practices (look for **City** or **Cities in the spotlight**).
- Identify accounting methods and metrics to measure and report positive, negative, and net emissions associated with compensation mechanisms (see in particular **Sections 6.2, 7 and 8**).
- Discuss opportunities and limits for comparability of results and delineate the criteria to avoid double counting (see in particular **Sections 5.2.3, 6.2, 6.3, and 7**).
- Promote alignment with international best practices, legislative developments around carbon removals, and regulations on land use, land use changes and forestry (see in particular **Sections 5.2, 6, 7, and 9**).
- Provide recommendations relevant to decision- and policy-making processes (throughout the document, condensed in **Section 10**).

This guidance does not intend to divert attention away from emissions reduction, which remains the primary focus of urban net-zero targets. Instead, it emphasises the importance of minimising residual emissions to the greatest extent possible in order to preserve carbon reservoirs for the compensation of unavoidable emissions. This approach is a fundamental principle of the Cities Mission, which views emissions compensation as a supplementary measure to achieve a net-zero balance by 2030, recognising that absolute zero may not be feasible at all times or through all means. It is also not among the aims of this guidance to be prescriptive in the methods, tools, or procedures to be followed to account for negative emissions, rather the emphasis is on the key principles and conditions to be met for a robust compensation strategy and accounting process. Nonetheless, existing suitable options and instruments are presented and discussed.

This guidance is primarily addressed to Mission Cities. It can be used to continuously inform the Climate City Contract (CCC) process, particularly in the following moments:

- Early stages of action planning and commitment definition, notably when defining the net-zero target and the residual emissions strategy (e.g., magnitude of residual emissions, type of carbon removals, type of credits, vintage of credits, timing)

— Iterative review of the CCC, in particular following any recalculation of residual emissions (due to updated data or methods) or any relevant technological, regulatory or financial advancements (including those enabling further emissions reduction at source).

Despite its conception within the framework of the Cities Mission, this guidance can be used by any local authority in the planning of a pathway to climate neutrality, as it describes key concepts, definitions, methods, and procedures, showcases best practices, and outlines guiding principles.

It should be emphasised from the onset that grey areas exist in the domain of negative emissions that require more testing and definition. On those occasions, this report provides general guidance on factors and options to take into consideration in the decision-making process, to the extent possible. No original methodology nor downscale of national methodologies is attempted in this document to fill any gaps.

As the role of emissions reductions and removals in the mitigation of climate change will change over time, this guidance offers the best knowledge and practice at the time of its delivery.

The guidance is complemented by a "Summary for Decision Makers" (Gevers Deynoot et al., 2026)[1], distilling key operational approaches for cities. The Summary provides a step-by-step decision-making roadmap, outlining recommended practices versus common mistakes and pitfalls, and is supported by visual elements. As a companion to the full guidance, the Summary is designed as a practical and accessible entry point for decision-makers by explicitly linking each decision-making step to the relevant sections of this guidance.

[1] Publication by Q2 2026, at the link provided in the references.

# 3 Start and end points in the journey to climate neutrality

A good understanding of the current level and sources of emissions represents the starting point of any transition to climate neutrality. An emissions inventory identifies the level and sources of emissions in a base year and within a specific accounting boundary. It informs target-setting, enables progress tracking, and eventually allows the climate neutrality status to be claimed.

As discussed in the Guidance on target setting and emissions inventories for the Climate-Neutral and Smart Cities Mission (NetZeroCities, 2023), ideally, a recent and comprehensive baseline GHG inventory serves this purpose in the Cities Mission (see Info Kit for Cities (European Commission, 2021g)). Robust business-as-usual (BAU) emission scenarios can also be used as a baseline. BAU scenarios should i) take into account the projected population and economic changes by the net-zero target year, ii) incorporate sector-specific trends and considerations, appropriate to the local context, iii) anticipate changes to sectoral energy intensity and carbon intensity of the electricity grid, and iv) be fully documented.

The geographic boundary of the emissions inventory should correspond to that of the climate neutrality target (e.g., Local Administrative Unit, Functional Urban Area), since residual emissions and eventually a climate neutrality claim will have to be verified against a consistent baseline emissions inventory. Accordingly, in the rest of this document, the expression "geographic boundary" is used to indicate the target geographic boundary, assumed equal to the emissions inventory geographic boundary. Consistently, the target boundary (that encompasses more broadly emissions scopes, sectors, sources, gases, and geographic boundary) is considered equivalent to the accounting boundary of the inventory.

The end point for a climate neutral city is to reach a zero emissions balance at the close of the target year (for Mission Cities, 2030). Cities should strive for absolute-zero, where emissions are fully abated at source. However, where reduction efforts are brought to their feasibility limit and emissions still exist, a net-zero balance is to be realised through compensation mechanisms (i.e., carbon removals and credits), complementing the portfolio of actions. Both absolute- and net-zero emissions constitute valid end points in the Cities Mission's framework. This milestone marks the beginning of a sustained state, where emissions are annually reduced to zero or below (net-negative) through reduction and compensation measures.

The ambition is to compensate only for those emissions that are impossible or very difficult to abate by the net-zero target year (i.e., residual emissions). Indicatively, residual emissions should stay below a ceiling of 20% of a recent baseline in the framework of the Cities Mission (European Commission, 2021g). This ceiling is an orientation not a prescription, meant to stress that emissions should be reduced as much as possible and the magnitude of what is compensated should be minimised at the benefit of reduction at source. No hard requirements are imposed in the context of the Mission as cities are encouraged to determine the actual percentage of residual emissions analytically and not through target-setting (see **Section 4**). This means that where the unavoidability of emissions is duly proved and discussed, residual emissions may exceed 20%. Equally, where achieving an emissions reduction beyond 80% by 2030 proves to be feasible, target and overall planning should reflect this ambition. The analysis and discussion of residual emissions should be repeated at each CCC iteration to reflect how the local and global context have changed in terms of emissions reduction options and constraints.

# 4 Residual emissions and the legitimacy of net-zero targets

Within the 100 Climate-Neutral and Smart Cities Mission framework, residual emissions can be defined as those emissions remaining at the close of the 2030 inventory period after all technically and economically feasible opportunities for emissions abatement have been implemented (where feasibility is tested against adequate theoretical frameworks (Steg et al., 2022)). Residual emissions should correspond to the total remaining emissions, i.e., the difference between baseline emissions and the potential emissions reduction that a city claims to achieve by 2030 through the portfolio of actions included in their CCC[2] and existing actions plans, if relevant. However, residual emissions may not always align with remaining emissions, particularly when the latter are determined through a target-setting process rather than a thorough analytical assessment. In such cases, the Climate Neutral Action Plans (CNAPs) may omit specific actions to reduce emissions from certain sources, despite the existence of feasible abatement options, and without disclosing the underlying constraints that prevent their implementation. In this scenario, there are no grounds for all remaining emissions to qualify as residual emissions and additional abatement efforts should be planned. Identifying residual emissions without questioning the reasons why emissions cannot be (further) reduced sheds uncertainty on the legitimacy of a net-zero target and increases the risk of excessive compensation, undercommitment or perceived greenwashing.

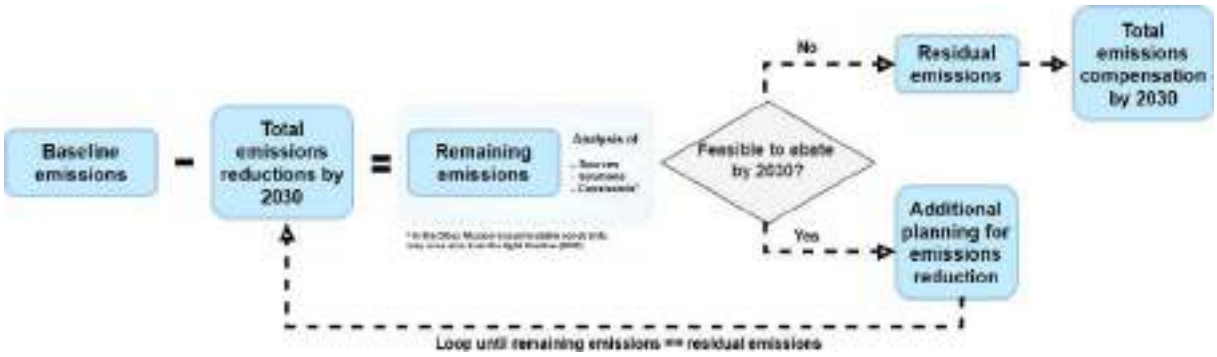
As displayed in **Figure 1** and further elaborated in **Figure 2**, a correct determination of residual emissions is an iterative process that involves:

- Comparing baseline emissions with the reduction potential of identified actions to quantify remaining emissions;
- Analysing remaining emissions to pinpoint sources, assess available solutions, and identify constraints (including those that may arise from the target timeline); and
- Continuously refining the action portfolio if further abatement is feasible, thereby increasing the total emissions reduction achievable by the net-zero target year.

Ideally, this iterative process should result in the convergence of remaining and residual emissions. The focus is on the nature of the emissions still present in the target year and whether these are truly unavoidable or hard-to-abate in the given local context.

[2] This includes actions and measures outside the CCC that are taken into account for reaching the net-zero target.

**Figure 1.** Remaining versus residual emissions in the strategic planning for the Cities Mission. Pathway towards convergence.




*Source: JRC analysis.*

Currently there is no standardised method for cities or other governance levels to identify their level of residual emissions or to systematically determine the difficulty of emissions avoidance or abatement.

In the Cities Mission, a practical framework is proposed (Ulpiani et al., 2024), structured around three main phases:

— **Identifying sources of emissions that cannot be brought to zero**. Firstly, cities should assess the sources of remaining emissions and identify those that are especially difficult to abate. These may range from high-rise buildings (whose cooling- and dehumidification-related emissions are particularly hard to reduce to zero) to historical buildings and heritage areas, from energy-intensive and high-temperature industries (e.g., cement, steel, plastics, aluminium, zinc, ceramics, bricks, chemicals) to waterborne navigation and aviation, from waste incineration to rice cultivation.

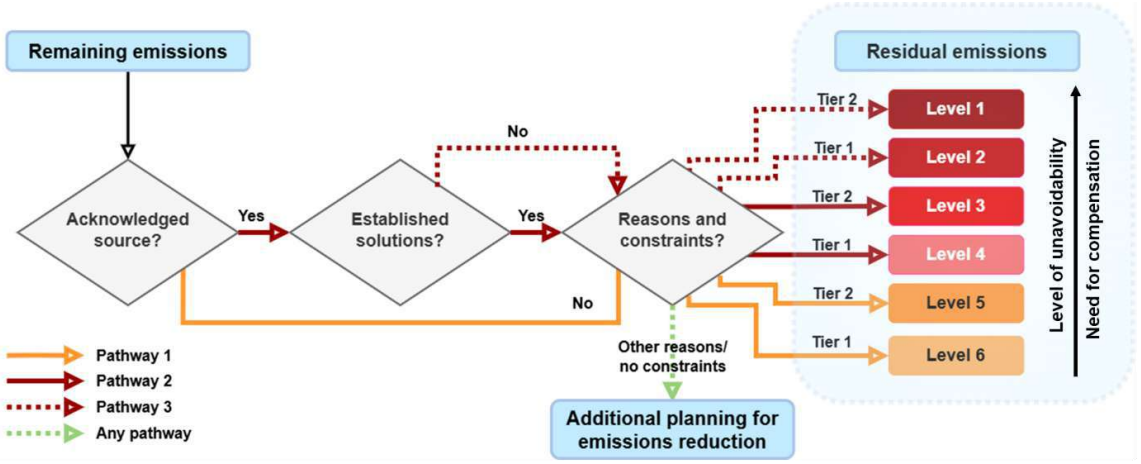
— **Exploring possible solutions**. Secondly, cities need to investigate a variety of potential solutions to see if there are any feasible ways to abate remaining emissions now or in the foreseeable future (with the net-zero target year standing as the time by which full implementation shall be achieved). Cities should (and/or should be supported to) scrutinise the arena of possible solutions across the CCCs of fellow Mission Cities or city networks, white and grey literature as well as across innovative companies and start-ups to determine whether any suitable option to reduce emissions exists and could be applied or transferred locally. An analysis of residual emission sources and potential solutions was incorporated in a 2018 Communication of the European Commission (European Commission, 2018c). In addition, a recent publication in Nature Climate Change shows that demand and technological interventions can substantially lower emission levels in hard-to-abate sectors (Edelenbosch et al., 2024). In their extended tables and Supplementary Material, the authors offer a list of potential solutions concerning aviation, shipping, industry, buildings, and agriculture. In 2027, cities will also have access to the IPCC Special Report on Climate Change and Cities, notably Chapter 3, which focusses on actions and solutions to reduce urban risks and emissions (IPCC, 2024).

— **Understanding the underlying reasons and limitations that prevent further reduction of emissions**. Thirdly, cities should critically examine the constraints that, even in the presence of potential solutions, hinder the feasibility of their implementation. In determining causality, cities should distinguish between obstacles that they can potentially overcome or significantly influence (here referred as tier 1 constraints) and those that are beyond their control or depend on higher government levels or external factors (tier 2). Tier 2 constraints support the argument that emissions are indeed residual. It is acknowledged that cities often face specific challenges that influence how they address residual emissions, especially when their timeline to achieve climate neutrality is more ambitious than that set at country level (as within the framework of the Cities Mission). City governments may not have the power to enact stricter emission standards than those set nationally and may confront insurmountable barriers that prevent them from taking more ambitious action within their jurisdiction. Additionally, there might be territorial issues, especially where efforts to reduce emissions could lead to competition over land use and tensions between rural and urban communities. Understanding whether local constraints hinder emission reduction efforts requires in-depth local knowledge and a solid theoretical framework, which should be clearly articulated in the CCC to justify the need for emissions compensation. It is worth stressing that the CCC is intended as an instrument to gather stakeholders and other levels of government around the climate neutrality target, to align efforts and remove any barriers or restrictions that come from stymied collaboration across governance levels.

The logical process behind the proposed methodology is presented in **Figure 2** (adapted from (Ulpiani et al., 2024)), together with a list of acknowledged sources of residual emissions, suitable abatement solutions and a non-exhaustive list of tier 1 and 2 constraints for reference. In the flow diagramme, the three procedural steps outlined above are translated into as many key questions, whose answers and their combinations give rise to different pathways. The end point is a 6-level scale to rate the difficulty of mitigating emissions. Level 1 indicates the strongest case for compensation where (1) the source of residual emissions is acknowledged, (2) no established solutions exist, and (3) the city is powerless against constraints (tier 2). Other combinations of points 1), 2), and 3) may lead to a lower degree of unavoidability that could still endorse a compensation rather than avoidance/reduction strategy in view of ensuring net-zero by the target year. The rationale should be discussed in the action plan to demonstrate the reasoning that the city has made in determining the magnitude and origin of residual emissions.

Through this approach, the levels of emissions unavoidability can be standardised while the process of answering each key question remains highly multi-factor and context specific. The proposed method is intended as a dynamic process, revisited regularly to keep pace with rapid changes in technology and the market.

**Figure 2**. Schematisation of the conceptual framework to establish (qualitatively) the level of unavoidability of remaining emissions and thus distinguish remaining from residual emissions. AFOLU: agriculture, forestry, and other land use; ICT: information and communication technology; IPPU: industrial processes and product use; PV: photovoltaic; RES: renewable energy source.




| Sources | Solutions |
|---|---|
| **Energy** | |
| - Historical buildings and heritage areas<br>- High-rise buildings | - Passive or climate-neutral (pre)heating/pre(cooling) systems<br>- Building electrification |
| **Transport** | |
| - On-road/off-road vehicles using fossil fuels<br>- Waterborne navigation<br>- Aviation | - Use of smaller vehicles<br>- Hybridisation, electrification, and design optimisation<br>- Advanced biofuels, hydrogen fuel cells, e-liquids and e-gas<br>- Renewable energy<br>- Smart urban planning (e.g. 15 min. city)<br>- Modal shift, promotion of walking and cycling<br>- Use of low-weight and energy unintensive materials |
| **Waste/wastewater** | |
| - Waste incineration and open burning | - Stricter bans on open burning of plant residues<br>- Circular economy models, industrial symbioses<br>- Recycled/reused/repaired materials instead of virgin materials<br>- Waste avoidance and/or reduction |
| **IPPU** | |
| - Energy-intensive and high-temperature industries<br>- Process emissions from chemical transformations | - Fuel switching options (to electricity, biomass, green hydrogen and e-fuels)<br>- Electrification of processes<br>- Alternative process technologies that use different chemical reactions |
| **AFOLU** | |
| -Enteric fermentation and manure handling<br>- Agricultural soils (e.g., fertilizers)<br>- Rice cultivation | - Selective breeding programmes<br>- Shifts in diets<br>- Reduction of untreated manure<br>- Efficient use of inorganic fertilizers<br>- Use of nitrification inhibitors<br>- Fallowing of organic soils (histosoils)<br>- Improved land management practices |

| Reasons/Constraints - Tier 1 |
|---|
| Lack of effective and sustainable policy at local level |
| Lack of multi-level coordination in the city governance |
| Insufficient administrative and/or operational capacity |
| Fragmentation of responsibilities |
| Fragmentation of infrastructure and technology ownership |
| Slow/disaggregated authorisation/financial processes |
| Investment lock-in (e.g., past investments to be recovered) |
| Lack of knowledge or know-how to eradicate emissions (locally) |
| Insufficient data collection |
| Lack of consolidated monitoring, reporting, and verification procedures |
| Lack of available land and/or conflictual uses of land |
| Growth schemes limitations/challenges |
| Lack of digitalisation/insufficient ICT access in remote areas |
| Difficulties in building collaborations between public and private sectors |
| Lack of industrial support in providing the necessary services |
| Lack of citizen participation and proactiveness |
| Slow behavioural transformation, including cultural barriers |
| Perceived technology performance uncertainty and risk |
| Lack of circularity/industrial symbiosis |

| Reasons/Constraints - Tier 2 |
|---|
| Lack of enabling policy at national and international level |
| Lack of multi-level coordination across governance tiers |
| Lack of market competition and/or frequent market failures |
| Prohibitive investment costs |
| Lack of funding/financing schemes |
| Lack of access to credit |
| Excessive requirements for liability insurance |
| Uncertainty about regulation and taxation |
| Regulatory restrictions |
| Authorisation processes not under the city's competence |
| Infrastructural and planning barriers/limitations |
| Insufficient flexibility in changing urban forms and functions |
| Geomorphic/topographic limitations/challenges |
| Climatic limitations/challenges |
| Unfavourable urban form and other characteristics impeding effective use of energy efficiency (e.g., natural ventilation) and RES (e.g., PV) measures |
| Lack of digital/smart instruments |
| Unavailability and cost-ineffectiveness of materials |
| Lack of available technologies to eradicate emissions |

*Source: (Ulpiani et al., 2024) (adapted with permission)*

Overall, the following key takeaways emerge:

— The magnitude of residual emissions should not be determined through a target-setting procedure, but rather through a critical analysis of local sources of emissions and associated constraints in abatement.

— Residual emissions should not be treated as an opaque concept where vested interests and/or expensive or politically inconvenient operations are concealed. Transparency on what will remain unabated is key to maintaining the credibility and legitimacy of net-zero commitments.

— Compensation rather than emissions reduction would be considered legitimate where emissions originate from hard-to-abate sources which cannot be lessened with current or foreseeable[3] solutions and are due to factors outside the city's remit or incompatible with near-term deadlines. This entails accurate scrutiny of the full spectrum of emissions reduction solutions (see, for instance **Box 1**). The rationale for ruling out reduction options should be clearly reported in the action plan.

— Defining the magnitude of residual emissions is an iterative process, responsive to technological advancements, market dynamics and situational evolutions[4].

Failing in this exercise comes with the risk of i) creating pressure for an oversized carbon removal infrastructure, with all the associated concerns in terms of feasibility as well as environmental, societal, and economic sustainability (Creutzig et al., 2015; Houghton et al., 2015) (refer to **Table 5** in **Section 6.3**), ii) limiting the benefits associated with emission reductions at source at the expense of local communities and future generations (Ou et al., 2021), and iii) increasing the reliance on technologies and techniques not yet mature on the market in the delivery of climate neutrality targets (Fankhauser et al., 2022). Further, distinguishing between remaining and residual emissions is critical in the face of the limited availability of e.g., acceptable-risk land-based carbon removals (Shindell & Rogelj, 2025). For instance, there is limited land available for afforestation and reforestation, and these carbon removals saturate over decades to centuries, so that the more used for near-term compensating easy-to-abate emissions the less remains for later use against hard-to-abate activities. Economically, using removals for easy-to-abate emissions may reduce costs for individual actors but increase system-wide expenses, as seen in sectors like aviation, which may require expensive synthetic fuels for net-zero air travel if removals are off the table (Shindell & Rogelj, 2025). As such, emissions compensation efforts should focus on hard-to-abate emissions and historical overshoot.

Following the proposed analytical approach would enhance the transparency of net-zero targets by fully revealing their true potential impact and would improve accountability among various government levels and external stakeholders.

**Box 1.** A candidate for residual emissions: the waste sector. Have you saturated your options?

Urban residual emissions may originate from any sector. Based on the responses from cities eligible to participate in the Mission, as reported in the Expression of Interest questionnaire, the transport sector is the most prevalent source of residual emissions, followed by Industrial Processes and Product Use (IPPU), stationary energy, waste, and Agriculture, Forestry, and Other Land Use (AFOLU) (Ulpiani et al.,

[3] The forecast horizon shall be compatible with the target year.

[4] For instance, the introduction of the European Emission Trading System 2 (ETS2) is expected to make certain decarbonisation options in the buildings and transport sectors, currently considered economically unfeasible, more viable and even attractive by imposing a cost premium on fossil fuels and providing access to significant funding opportunities (e.g., the Social Climate Fund).

2023). In this box, the waste sector is taken as an example to showcase how cities can interrogate the solutions space to reduce emissions before resorting to forms of emissions compensation.

The largest contributors to waste-management GHG emissions are $CH_4$ from landfills, $CO_2$ from incineration and other lifecycle emissions through collection and recycling, and CFC from waste appliances through specific treatment. By 2050 waste emissions are expected to be reduced by 71% compared to 2021 levels (average at country-level) (Bogner et al., 2007; H. B. Smith et al., 2024). The full implementation of the hierarchy of waste management (IPCC, 2014c), associated Best Available Techniques (BAT, in particular for F-gases recovery) (Pinasseau et al., 2018) and best environmental management practices in the waste management sector (European Commission, 2020d), are precious mechanisms to curb waste-related emissions.

However, a number of emissions streams ($CO_2$ from incineration of waste that cannot be conventionally re-used or recycled, $CH_4$ and $N_2O$ from waste and wastewater management infrastructures) will remain in the absence of more specific measures. Out of the total claimed residual emissions for COP Annex I countries, waste will contribute to 9% without innovative and targeted actions (H. B. Smith et al., 2024). Globally, waste-related $CH_4$ claimed residual emissions have been estimated at 1 $GtCO_2$-eq/yr (Lamb, 2024).

Cities pursuing ambitious net-zero pathways can walk the extra mile and avoid or reduce to negligible levels their waste-related remaining emissions by adopting or strengthening the following targeted mitigation measures or equivalent ones:

— Integrated measures to avoid or minimise $CH_4$ and $N_2O$ from humid biodegradable waste:

  - Humid organic waste, including sewage sludge, is fully separately collected at source and processed in anaerobic digesters (Bogner et al., 2007).
  - Biogas from anaerobic digesters is upgraded to biomethane for grid injection or storage; sewage, waste facilities and biogas networks can adopt best practices to avoid $CH_4$ and $N_2O$ leaks and degassing (Buffi et al., 2024).
  - Digestate from anaerobic digesters is composted to produce a soil improver (Soudon et al., 2024), which then replaces nitrogen synthetic fertilisers in city soils (agricultural or garden areas), thereby reducing $N_2O$ emissions (Gao et al., 2024).
  - In wastewater treatment plants, aerated zones are created and operational strategies (availability of dissolved oxygen, chemical oxygen demand and nitrogen ratio) are shaped to avoid the stripping of $N_2O$ emissions, which currently occurs mainly during biological nitrogen removal (IPCC, 2014c).
  - All MSW (municipal solid waste) landfills are activated. Final cover and an efficient gas extraction system (using vertical wells and/or horizontal collectors) are adopted in closed MSW landfills. Landfill biogas is either upgraded to biomethane or converted into usable energy, flaring only when the amount of processed $CH_4$ does not allow any another use. Mature landfills are further covered with compost-amended 'biocovers' engineered to optimise oxidation of residual $CH_4$ flows and potentially atmospheric $CH_4$ (Bogner et al., 2007).

— Advanced thermal treatment (e.g., hydro-pyrolysis, gasification) can replace incineration, while still maintaining the essential service of removing unwanted substances from society and economy (Bogner et al., 2007). From a lifecycle GHG emissions perspective, physical or chemical recycling outperform energy recovery from waste (Garcia-Gutierrez et al., 2025). Therefore, the following measures can be adopted:

- Recycling plastic waste (from municipal, construction/demolition and industrial waste, where appropriate). Mechanical, physical, or chemical recycling can replace effectively waste incineration, co-incineration, and refuse-derived fuel production. The optimal process depends on the nature of the waste feedstock (CRE, 2023; Garcia-Gutierrez et al., 2025; Lee et al., 2022; Nixon et al., 2024; Peplow, 2025).
- Treating mingled and mixed residual plastics, in advanced chemical recycling plants (e.g., gasification, pyrolysis, hydro-pyrolysis plants) to produce basic chemicals (e.g., methanol, ethylene) for circular chemicals production (Lee et al., 2022; Peplow, 2025).
- Re-refining or converting used mineral oils and solvents into chemicals (García-Gutiérrez et al., 2025; IFEU, 2018).

— Consider introducing specific obligations in environmental permits for industrial facilities, to scale up synergies in municipal and industrial waste management when appropriate to boost the measures listed above (IPCC, 2014c).

Mitigation measures can also be integrated with removal measures to offer additional cross-sectoral opportunities, stemming from the use of recycled material or products, by:

— Using biofuels and/or biogases generated from bio-waste in waste management vehicles and other city-managed vehicles (buses, ambulances, emergency vehicles, excavation machineries…) when possible, during the transition to electric vehicles.

— Replacing natural gas with biomethane to reduce emissions from grid gas consumption in the city.

— Implementing quality-assured soil improvers, such as:

- Compost, composted digestate from anaerobic digestion, to enhance soils health and quality while replacing fertilisers and thus reducing $N_2O$ emissions (Gao et al., 2024).
- Biochar from pyrolysis of biogenic waste (e.g., park and garden waste, selected wood waste), to store carbon into soils (see **Annex 2**)

Some integrated measures could result in net negative emissions within the city territory owing to their carbon removal effect:

— Biocovers of legacy landfills (Bogner et al., 2007).

— Use of biochar and/or bioenergy with carbon capture and storage (see **Annex 2**).

Economy of scale for some advanced mitigation measures (e.g., certain chemical recycling facility) is needed for smaller cities; cities can overcome this constraint when contracting or commissioning waste treatment facilities, by pooling resources and joining forces with either neighbouring cities or industrial waste producers to reach the proper facility scale.

If the above measures are feasible to implement within relevant timelines but not considered in the planning, the associated emissions are not legitimately classified as residual.

Regardless of the inclusion of any analysis/rationale for ruling out the reduction of remaining emissions, it is imperative that the CCC contains a list of actions and a residual emissions strategy covering all remaining/residual emissions, so that the absolute- or net-zero target can be still verified. Transparency around residual emissions vis-à-vis target exclusions is also critical for target verification (see **Box 2**).

**Box 2**. Residual emissions versus target exclusions

In formulating their climate neutrality target, Mission Cities may propose to exclude one or more district(s) or emission sources from the 2030 deadline, where duly justified (European Commission, 2021g). In this case, cities should commit to a strategy of climate neutrality for these exclusions as soon as possible and no later than 2050.

Hence, residual emissions that fall within the city's target need to be compensated already by 2030. Excluded emissions have a different timeline and can be reduced, avoided, or compensated by 2050.

# 5 Emissions compensation mechanisms

Within the framework of the Cities Mission, residual emissions can be compensated through i) the removal of GHGs from the atmosphere via deliberate activities within the boundary (see **Section 5.1** "In-boundary carbon removals", **Box 3** and the **Annexes**) and ii) out-of-boundary carbon removal credits[5] (**Section 5.2**), where the term "carbon" encompasses the wider concept of carbon-equivalence (thus incorporating also other GHGs beyond $CO_2$).

In general, four criteria could be used to determine whether a greenhouse gas removal (GGR) occurs in response to a deliberate anthropogenic activity (Tanzer & Ramírez, 2019):

- Physical GHGs are removed from the atmosphere, not from fossil sources.
- The removed gases are stored out of the atmosphere in a manner intended to be durable.
- Upstream and downstream GHG emissions associated with the removal and storage process, such as biomass origin, energy/gas/co-product use are comprehensively estimated and included in the emission balance.
- The total quantity of atmospheric GHGs removed and permanently stored is greater than the total quantity of GHGs emitted to the atmosphere.

Therefore, the origin of the greenhouse gases shall be atmospheric, either capturing them directly from ambient air or indirectly from biomass, and the storage durability of the natural or chemically engineered sink should be meaningful. For this reason, **Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) technologies cannot result in carbon removal when the $CO_2$ is of a fossil origin**. This is the case with point-source emissions from fossil fuel power plants and heavy industry. This form of CCS reduces (or better yet avoids) emissions, therefore contributing to the overall emissions reduction target. CCS and CCU can only be considered a removal method when the $CO_2$ is atmospheric and durably stored in geological reservoirs or products (IPCC Working Group III, 2022a). Using, re-using or recycling biogenic $CO_2$ or $CO_2$ captured from ambient air to produce short-lived products is not an admissible strategy to compensate for residual emissions.

**Box 3.** This cannot be stressed enough: carbon removals originate from deliberate anthropogenic activities

Carbon removals shall stem from deliberate anthropogenic activities, i.e., intentional actions that extend beyond the contribution of the natural carbon cycle. Accordingly, Mission Cities can account for negative emissions achieved through the enlargement or enhancement of natural sinks as a strategy to address residual emissions within their territories, as outlined in the Info Kit for Cities (European Commission, 2021g). Conversely, existing carbon sinks whose storage is not amplified by deliberate activities do not count toward negative emissions. The key is to clearly evidence how negative emissions originate from deliberate actions that produce additional benefits beyond the natural cycle. Cities shall demonstrate tangible efforts to expand carbon stocks by enhancing the health of trees or improving management practices for existing sinks to be considered in the computation of negative emissions. Cities can also leverage soft measures, such as early warning systems, citizen engagement, and capacity-building

[5] Out-of-boundary removals can be accounted for as negative emissions only if they go through a crediting process. This does not exclude the possibility for cities to buy credits generated inside their boundary.

activities to sustain their claims, provided they show a positive impact in terms of enlargement or enhancement of local sinks. Claiming negative emissions from existing forests and trees without proactive measures risks accusations of greenwashing. Only the additional anthropogenic impact can be counted as negative emissions. Utilising modelling tools to compare the effects of new practices versus BAU is encouraged to clearly demonstrate the anthropogenic effect. The preservation of existing sinks from natural degradation or wildfire damage represents a form of emissions avoidance rather than negative emissions and can contribute to the overall emissions reduction target. The impact is only visible when compared to a BAU emissions baseline that forecasts the carbon sink reduction associated with degradation and damage.

Overall, in the Cities Mission, cities are invited to propose a well-rounded balance between actions to improve existing sinks and actions that enhance or enlarge sinks to maximise their contribution to climate goals.

When the only GHG concerned is $CO_2$, it is customary to use the term carbon dioxide removal (CDR). CDR refers to "anthropogenic activities removing $CO_2$ from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural $CO_2$ uptake not directly caused by human activities" (IPCC, 2018a). CDR strategies and technologies are the most widely documented and implemented forms of GGR across all governance scales.

In its 2022 Mitigation of Climate Change report, the IPCC has defined three roles for CDR to complement GHG emissions reduction: i) limiting net emissions in the short term, ii) counterbalancing residual emissions from 'hard-to-abate' sectors to help reach net-zero emissions in the mid-term, and iii) achieving net negative $CO_2$ emissions in the long term when removals are in excess of annual residual emissions (IPCC, 2022a). Mission Cities can use CDR to compensate for residual emissions, after maximising the emissions reduction potential within the target boundary, but are advised to also consider the short- and long-term roles of CDR when planning their residual emissions strategy. Implementation of a residual emissions strategy requires the city to decide which CDR methods to pursue, either as in-boundary removals or through the procurement of CDR credits. Considerations such as the scale and timing of deployment, management of sustainability constraints and challenges, the social legitimacy of certain approaches, are all important factors to control. There are many different CDR methods and associated implementation options, with different timescales, opportunities and risks, co-benefits or adverse side effects (see **Annexes 1 and 2** and **Sections 5.1 and 6**). A residual emissions strategy should manage these considerations through effective CDR governance and policies (IPCC, 2022a).

Durability or permanence of the carbon sink (see **Box 4**) is a vital criterion for determining the eligibility of the compensation mechanism. Depending on the CDR method, the removal can be temporary (several decades) or durable, also referred to as permanent (several centuries). The EU Carbon Removal and Carbon Farming (CRCF) Regulation (see **Section 9**) defines "permanent carbon removal" as "any practice or process that, under normal circumstances and using appropriate management practices, captures and stores atmospheric or biogenic carbon for several centuries, including permanently chemically bound carbon in products, and which is not combined with enhanced hydrocarbon recovery". The Regulation defines "temporary carbon removal" as activities that capture and store $CO_2$ from the atmosphere for a time period that is less than several centuries, encompassing activities like carbon farming and storage in long-lasting products (European Parliament and Council, 2024b).

**Box 4.** Carbon sinks and carbon removals

The IPCC defines a carbon 'sink' as "a reservoir (natural or human, in soil, ocean, and plants) where a greenhouse gas, an aerosol or a precursor of a greenhouse gas is stored" (IPCC, 2018a). The term sink signifies that it acts as a net absorber. The same reservoir can also act as a source of emissions when it is a net emitter.

In the value chain of a carbon removal project, sinks can cover both the removal and storage section or just the storage medium. When the sink covers the full project value chain, interventions focus on creating, restoring or enhancing the carbon absorption and retention qualities of the sink. This is primarily the case for natural sinks. Reforestation, afforestation, enhanced forest management, and enhanced land management are all examples of deliberate human activities that focus on natural sinks which remove and store carbon in a contained process. Chemically engineered sinks are storage mediums that are often separated from the removal activity. This is the case, for example, of carbon removal project value chains involving Direct Air Capture (DAC) facilities that remove $CO_2$ out of the atmosphere for storage or use.

The value of removals exists in relation to climate objectives and time horizons. In practice, permanence is not about physical permanence of removals, rather permanent means that the removed carbon is stored for an equal or longer amount of time than a defined time horizon. The definition of permanence or durability is the result of a political decision as there is currently no clear scientific basis to determine a clear-cut threshold for durability, nor consensus among policymakers (S. M. Smith et al., 2023). As shown in **Figure 3**, the IPCC categorises CDR methods in decades to centuries, centuries to millennia, and ten thousand years or longer (IPCC Working Group III, 2022a). Meanwhile, a diversity of minimum thresholds for storage is used in public policies and carbon crediting programmes, ranging from 25 years up to 100 or 1000 years (S. M. Smith et al., 2023). Some programmes, like those managed by the U.S. Department of Energy, have used a 100-year threshold for CDR projects. Under Article 6.4 of the Paris Agreement, CDR projects eligible for the carbon crediting mechanism shall store the carbon for a climate-relevant timescale, which is understood as at least 200-300 years. The advanced market mechanism Frontier sets a 1,000-year threshold.

It is argued by some academics and market operators that the 1,000-year timescale should be preferred to completely neutralise a ton of residual fossil $CO_2$ emissions in a net-zero emissions framework and realise sustainable temperature stabilisation. As its main function, CDR shall have a cooling effect that is equal to the $CO_2$-induced warming of residual $CO_2$ emissions into 'perpetuity'. Since the global warming effect of fossil $CO_2$ emissions is long-lasting (as the molecules remain in the atmosphere for millennia), the re-emission of stored $CO_2$ (also known as "reversal") may lead to a return of the warming effect long after the world has achieved net-zero emissions (Brunner et al., 2024).

The time scale of carbon storage is a critical parameter. The storage medium largely determines the storage duration. $CO_2$ stored in ocean reservoirs, through methods such as enhanced weathering, ocean alkalinity enhancement or ocean fertilisation (see **Annex 2**), tends to stay for hundreds if not thousands of years. The same applies for CDR methods storing the $CO_2$ in geological formations, such as saline aquifers or retired oil and gas reservoirs, which is the case for Bio Energy with Carbon Capture and Storage (BioCCS or BECCS) or Direct Air Capture with Carbon Storage (DACCS) (see **Annex 2**). Because of their high storage integrity, these options are typically less vulnerable to reversal than carbon sequestered in the soil or vegetation (see **Annex 1**). Biogenic carbon from biomass is furthermore stored for a longer time with higher storage integrity than soil sequestration when it comes in the form of wood-based or other bio-based construction materials,

such as hemp-based concrete, used for buildings. When the biomass is turned into biochar through pyrolysis and used in soils, cement and other construction materials, or if it becomes part of chemical products made from biomass, it may represent high storage durability, in the order of centuries, depending on the pyrolysis process that is applied (Fuss et al., 2018; Minx et al., 2018).

As the integrity of storage differs, so do the management requirements (Mac Dowell et al., 2022). A city's decision on the CDR methods to pursue should take this into account, as the burden to ensure storage integrity may over time become a public responsibility, including Monitoring Reporting and Verification (MRV) requirements and the question of liability for failed storage and reversal (see **Box 5**).

**Box 5.** Monitoring Reporting and Verification of carbon removals

MRV of the carbon removal process is vital for determining the integrity of CDR projects and their eligibility for use as a compensation mechanism by Mission Cities. MRV protocols have been developed for a wide range of CDR methods and applications, though not for all and not in all cases is the protocol considered robust. The complexity of MRV varies significantly depending on the open- and closed-system nature of the specific CDR options considered. Open-system strategies, such as enhanced rock weathering or ocean alkalinity enhancement, involve a higher degree of natural biogeochemical processes to capture and/or sequester the $CO_2$ that may be more or less challenging to monitor and verify. Similarly, CDR methods like wetland restoration or mangrove forest conservation may require MRV protocols that account for the dynamic and often unpredictable nature of these ecosystems. Closed-system strategies, such as BioCCS with storage in geological reservoirs, entail a high degree of human control and engineering, with storage taking place in a controlled environment which may facilitate MRV processes (Mac Dowell et al., 2022). The complexity of MRV also depends on the governance of CDR. Strategies involving multiple stakeholders, such as soil carbon sequestration through regenerative agriculture, may require more articulated and decentralised MRV protocols to account for e.g., variations in farming practices and soil types. At the same time, the contribution of various stakeholders may facilitate local data collection and monitoring, potentially increasing the accuracy of the carbon removal estimations over time.

Examples of MRV requirements in different removal strategies (as defined in the **Annexes**) include:

- Afforestation/reforestation: monitoring tree growth, soil carbon stocks, and forest biomass.
- Ocean fertilisation: accounting for ocean currents, nutrient cycling, and phytoplankton growth.
- Enhanced rock weathering: monitoring weathering rates, $CO_2$ uptake, and soil carbon stocks.
- BioCCS: monitoring $CO_2$ injection rates, storage capacity, and potential leakage.
- DACCS: monitoring $CO_2$ capture rates and storage in real-time.
- Soil carbon sequestration: accounting for variations in farming practices, soil types, and regional climate conditions.
- Wetland restoration: monitoring water levels, soil carbon stocks, and vegetation growth in dynamic ecosystems.

These examples illustrate the importance of developing tailored MRV protocols that take into account the specific characteristics and challenges of each CDR strategy, in order to ensure the integrity and effectiveness of CDR projects and their eligibility for use as a compensation mechanism by cities. The MRV feasibility of the main CDR options is mapped in **Table 2**.

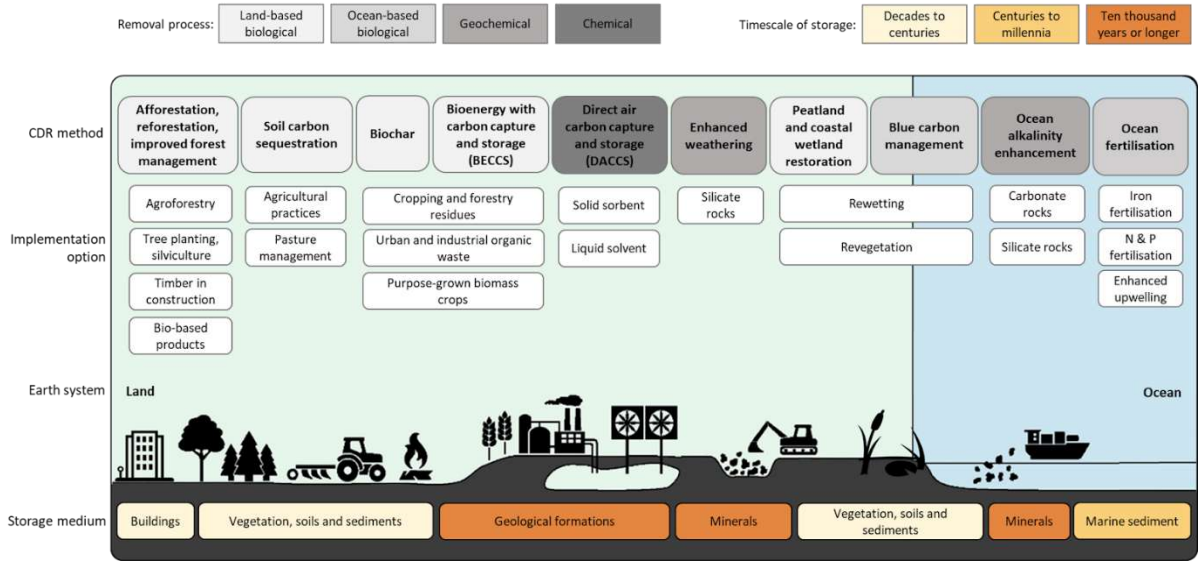
In the Cities Mission, permanence of removals is encouraged to avoid claims of climate neutrality that may be lost in the short term. However, in the fight against climate change, all CDR methods have a function, whether the storage is for several decades or millennia (**Figure 3**). From the perspective of climate change mitigation, the added value of temporary removals is especially strong when they coincide with peak warming. This is because they can help limit the maximum temperature increase by realising a "peak shaving" effect that reduces the severity of climate change impacts when temperatures are the highest, even if the carbon is ultimately released back into the atmosphere (Mac Dowell et al., 2022). The value proposition strengthens significantly when temporary removals are complemented with permanent removals. Without this mitigation effort, the temporary removal would merely delay the onset of higher temperatures, rather than affecting peak warming. Hence, when temporary CDR is part of a residual emissions strategy, this should be accompanied by a commitment to replace them with new temporary future removals or durable CDR by the time of the re-release of the $CO_2$. Moreover, temporary removal methods involving carbon sequestration in ecosystems and on agricultural lands can realise non-$CO_2$ biophysical effects that negatively impact global warming (e.g., decrease in surface albedo). This effect can significantly counter the climate effect of the sequestered carbon (Matthews et al., 2022).

For the purpose of counterbalancing emissions, Mission Cities are recommended to resort to carbon removals only to compensate for unavoidable emissions and are encouraged to take into account the like-for-like principle. This carbon accounting principle is an important yardstick to understand the use cases of both temporary and permanent removals. The principle applies equally to the development of in-boundary carbon sinks as it does to the purchase of out-of-boundary carbon credits to balance residual emissions. The like-for-like principle ensures a durable state of net-zero emissions by rebalancing carbon fluxes with the appropriate removals and stabilising both surface carbon pools (atmosphere, biosphere and oceans) and carbon pools in the lithosphere (rocks, minerals and sediments). Like-for-like removals are defined by the UNFCCC Race to Zero campaign as “when a source of emissions and an emissions sink correspond in terms of their warming impact, and in terms of the timescale and durability of carbon storage” (UNFCCC, 2021). In essence, this principle requires like-for-like counterbalancing of the source of GHG emissions and the sinks in terms of the origin (biogenic versus geological) and the gas atmospheric residence time (Brunner et al., 2024). In practice, this means that emissions from extracting and burning fossil fuels in the form of oil, gas or coal and their derivatives shall be balanced by permanent storage of removed carbon, instead of using natural sinks with a shorter carbon cycle. Short-duration GHGs such as methane and biogenic emissions can be compensated with temporary removals in natural carbon sinks such as forests and soils. The integrity of a residual emissions strategy is significantly strengthened with like-for-like compensation (M. R. Allen et al., 2022). Tracking progress requires a city to separate the accounting between biogenic and permanent emissions and removals.

Given the importance of like-for-like compensation, it is crucial to consider the development stage and suitability of various CDR methods. While some CDR methods have not yet been demonstrated at scale, and many have not been considered for deployment in the built environment, nature-based solutions have been tried and tested, offering a more cost-effective and viable option in the short run. However, their use for compensating for residual emissions from hard-to-abate sectors is limited when applying the like-for-like principle. In contrast, permanent CDR methods are expected to become increasingly relevant in the mid-to-long term, as they offer storage capacity and duration that exceeds that of traditional carbon removal methods such as forestry and soil sequestration (EPRS, 2021; S. M. Smith et al., 2023).

It should be noted that, outside net-zero targets, specific CDR methods may be targeted for other reasons than exclusively their removal potential. Cities are encouraged to take a holistic approach, with a view of maximising co-benefits and minimising trade-offs (see **Section 6.4**). Targeting removal methods for their co-benefits may help increase the social acceptance and political feasibility of an intervention by emphasising the positive impacts for citizens.

**Figure 3**. Carbon dioxide removal taxonomy. Methods are categorised based on removal process (grey shades) and storage medium (for which timescales of storage are given, yellow/brown shades). Main implementation options are included for each CDR method. Note that specific land-based implementation options can be associated with several CDR methods, for example, agroforestry can support soil carbon sequestration and provide biomass for biochar or BioCCS.




*Source: (IPCC, 2022b)*

This guidance considers a wide range of options available in the current landscape of carbon removal methods, presented in detail in **Annexes 1 and 2**, and options for non-$CO_2$ removal (**Annex 3**) which also serve as scientific background. A synoptic illustration of how the different options compare is presented in **Section 5.1** while the deployment potential in urban environments is outlined in **Section 5.1.1** by looking at specific applications.

In the Cities Mission, where removals occur within the target boundary as a result of human intervention, they can righteously and directly be used to compensate for residual emissions (see **Box 3 and Section 5.1**). If the same activity then undergoes a crediting process to be sold to third parties, carbon sinks take the form of carbon credits and should be carefully treated as discussed in **Section 6.2** and following the key requirements outlined in **Section 5.2**, similarly to out-of-boundary carbon removal credits. Various principles apply to both in-bound removals and out-of-boundary carbon removal credits to ensure that they represent genuine instruments of climate action. This is discussed in **Section 6**.

## 5.1 In-boundary carbon removals

Several types of GGR can be implemented within a city's net-zero target boundary. These are presented individually in the **Annexes**, with CDR options divided according to their temporary or permanent nature. In this section, a synoptic comparison across the different options is presented to support decision-making (**Table 1** and **Table 2**). **Table 1** illustrates the CDR methods categorised by their removal mechanism and storage location. Cell colours are used to highlight different $CO_2$ storage options (integrated and separate). An integrated storage mechanism refers to a CDR strategy where the capture and storage of $CO_2$ occur within the same system or process. This means that the $CO_2$ is captured and stored in a unified manner, often utilising the same infrastructure or technology. Afforestation/reforestation is an example of an integrated storage mechanism, where trees absorb $CO_2$ from the atmosphere through photosynthesis and store it in their biomass and soil. Integrated storage mechanisms often simplify operations, reduce logistical complexities and overall costs, as the capture and storage processes are intertwined. Furthermore, integrated storage mechanisms tend to be more environmentally friendly and sustainable, as they often rely on natural processes. On the other hand, a separate mechanism involves distinct processes for capturing and storing $CO_2$. This approach requires separate infrastructure, technologies, or systems for each step, which can be located in different areas. For example, DACCS technology captures $CO_2$ from the air, which is then transported to a separate location for storage, such as a geological formation. One of the main drawbacks is the higher logistics costs associated with transporting captured $CO_2$ from the capture site to a storage location. This can be a complex and energy-intensive process, requiring significant infrastructure and resources. Additionally, separate mechanisms may require more land, materials, and equipment, which can increase the overall cost and environmental impact of the carbon removal strategy. However, separate mechanisms can also offer greater flexibility and scalability, as the capture and storage processes can be optimised and expanded independently. Moreover, in contexts of multilevel governance and existing usable infrastructure, such as in countries with historical oil and gas resources, separate storage mechanisms may be more feasible and easier to implement (Alcalde et al., 2025). For instance, repurposing existing oil and gas infrastructure for $CO_2$ storage can reduce costs and accelerate deployment, while also leveraging the expertise and regulatory frameworks already in place. Ultimately, the choice between an integrated storage mechanism and a separate mechanism depends on the specific CDR method, political and regulatory context, and available resources.

**Table 1**. CDR methods categorised by their removal and $CO_2$ storage mechanisms. Methods with integrated storage are highlighted in green and those requiring a separate storage mechanism in blue.

| | | **CDR method** | | |
|---|---|---|---|---|
| | | **Increased biological uptake** | **Natural inorganic reactions** | **Engineered removal** |
| **Storage location** | **Land vegetation (living)** | Afforestation, reforestation, and forest management; Agroforestry; Wetlands restoration. | | |
| | **Soils and land vegetation (dead)** | Soil carbon sequestration; Biochar | Enhanced terrestrial weathering | |

| | | | | |
|---|---|---|---|---|
| | **Geological** | BioCCS | Mineral carbonation at surface | DAC + geological storage; DAC + sub-surface mineral carbonation |
| | **Oceans** | Ocean fertilisation | Ocean alkalinity enhancement | DAC + deep ocean storage |
| | **Built environment** | Durable harvested wood products | | |

*Source: JRC analysis (adapted from (The Royal Society, 2018)).*

**Table 2** shows the summary of status, costs, removal potential, risks and impacts, co-benefits, and feasibility/guidance provision in terms of monitoring, reporting and verification. It relies on scientific information, recently condensed in a number of documents (Babiker et al., 2022; S. M. Smith et al., 2023). It does not refer to urban-specific implementations, but to the general CDR method described. Adverse effects and co-benefits of urban implementation approaches are presented in **Table 5**. In general, information on e.g., risks, impacts and co-benefits is context specific.

**Table 2**. Summary of CDR methods and urban-specific implementation options. Technology Readiness Level (TRL, ranging from 1 indicating a technology which exists only in terms of basic outlined principles to 9 for operationally proven systems), cost and global mitigation potential estimations from literature, potential risks and negative impacts, co-benefits and feasibility of monitoring, reporting and verification (MRV) of net carbon dioxide removal. MRV is assessed for both capture and storage steps in terms of i) simplicity/precision of quantifying the amount of carbon removed (low/medium/high/very high, based on expert judgement (S. M. Smith et al., 2023)) and ii) existence or not of an MRV methodology in the IPCC Guidelines for National Greenhouse Gas Inventories (yes/no). "I.d." stands for insufficient data.

| CDR method | TRL | Cost (USD/ $tCO_2$) | Global mitigation potential ($GtCO_2$/ year) | Examples of urban in-boundary Implementation | Potential risks and impacts | Co-benefits | MRV feasibility |
|---|---|---|---|---|---|---|---|
| **Afforestation/ reforestation** | 8-9 | 0-240 | 0.5-10 | • Expanding urban forests and parks<br>• Planting street trees and green corridors | Reversal of carbon removal through wildfire, disease, pests; reduced catchment water yield and lower groundwater level if species and biome are inappropriate; competition for land with biodiversity conservation and food production | Enhanced employment and local livelihoods, improved biodiversity, improved renewable wood products provision, soil carbon and nutrient cycling. Possibly less pressure on primary forest | Capture: high, yes<br>Storage: high, yes |
| **Improved forest management** | 8-9 | i.d. | 0.1-2.1 | • Improved management of urban forests and parks (e.g., through lengthening forest rotations) | Risk of reversal. If improved management is understood as merely intensification involving increased fertiliser use and introduced species, then it could reduce biodiversity and increase eutrophication and upstream GHG emissions | In case of sustainable forest management, it leads to enhanced employment and local livelihoods, enhanced biodiversity, improved productivity | Capture: medium, yes<br>Storage: medium, yes |
| **Agroforestry** | 8-9 | i.d. | 0.3-9.4 | • Integration of trees and shrubs into urban agricultural areas | Risk that some land area is lost from food production; requires high skills; trade-offs with agricultural crop production | Enhanced employment and local livelihoods, variety of products, improved soil quality, more resilient systems, enhanced biodiversity | Capture: medium, yes<br>Storage: medium, yes |
| **Soil carbon sequestration in croplands and grasslands** | 8-9 | -45-100 | 0.6-9.3 | • Land management practices to increase carbon in urban cropland and grassland soils | Risk of increased nitrous oxide emissions due to higher levels of organic nitrogen in the soil; risk of reversal of carbon sequestration | Improved soil quality, resilience and agricultural productivity | Capture: medium, yes<br>Storage: low, yes |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Terrestrial wetland restoration** | 8-9 | i.d. | 0.5-2.1 | • Restoration of wetlands like peatlands for cities with dried or degraded wetland areas | Reversal of carbon removal in case of drought or other disturbance; risk of increased methane emissions; competition for land for food production | Enhanced employment and local livelihoods, increased productivity of fisheries, improved biodiversity, soil carbon and nutrient cycling | Capture: low, yes<br>Storage: low, yes |
| **Coastal wetland (blue carbon) management** | 2-3 | i.d. (estimates in the range 100-10,000) | <1 | • Planting or restoration of tidal marshes, mangroves and seagrasses for coastal cities | If degraded or lost, coastal blue carbon ecosystems are likely to release most of their carbon back to the atmosphere. The full delivery of the benefits at their maximum global capacity requires years to decades to be achieved. Potential for sediment contaminants, toxicity, bioaccumulation and biomagnification in organisms; issues related to altering degradability of coastal plants; use of subtidal areas for tidal wetland carbon removal; effect of shoreline modifications on sediment redeposition and natural marsh accretion; abusive use of coastal blue carbon as means to reclaim land for purposes that degrade capacity for carbon removal | Potential for many non-climatic benefits and ecosystem-based adaptation, coastal protection, increased biodiversity, reduced upper ocean acidification; could potentially benefit human nutrition or produce fertiliser for terrestrial agriculture, anti-methanogenic feed additive, or as an industrial or materials feedstock | Capture: low, no<br>Storage: medium, no |
| **Biochar** | 6-7 | 10-345 | 0.3-6.6 | • Urban biogenic waste conversion into biochar<br>• Soil amendment of urban green spaces<br>• Structural soil for green stormwater infrastructure<br>• Biochar additions to construction materials, such as cement-based materials<br>• Use of biochar for heating or energy production | Particulate and GHG emissions from production; biodiversity and carbon stock loss from unsustainable biomass harvest; competition for biomass resource | Increased crop yields and reduced non-$CO_2$ emissions from soil; resilience to drought | Capture: high, yes<br>Storage: medium, yes |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Durable harvested wood products** | 8-9 | i.d. | 0.2-1.3 | • Timber in construction (cross-laminated timber, glulam, wooden bridges, mass timber construction and urban landscaping) | Increased fertiliser use; biodiversity loss; increased eutrophication; fire risk | Reduced ecological toxicity, improved human health and wellbeing and reduced duration of construction compared with alternative building materials. | Capture: high, yes<br>Storage: medium, yes |
| **BioCCS** | 5-6 | 15-400 | 0.5-11 | • Combustion of urban biogenic waste with $CO_2$ capture<br>• Biofuel production with $CO_2$ capture<br>• Wastewater treatment with $CO_2$ capture | Competition for land and water resources, to grow biomass feedstock. Biodiversity and carbon stock loss if from unsustainable biomass harvest | Reduction of air pollutants; fuel security, optimal use of residues, additional income, health benefits and if implemented well can enhance biodiversity, soil health and land carbon | Capture: high, yes<br>Storage: high, yes |
| **DACCS** | 6 | 100-300 | 5-40 | • Modular direct air capture in buildings | Increased energy and water use (and associated emissions) | Water produced (solid sorbent DAC designs only) | Capture: very high, no<br>Storage: high, yes |
| **Enhanced weathering** | 3-4 | 50-200 | 2-4 | • Spreading of suitable rocks and minerals into dedicated urban soils | Mining impacts; air quality impacts of rock dust when spreading on soil; potentially increased emissions from water supply and energy generation | Enhanced plant growth, reduced erosion, enhanced soil carbon, reduced soil acidity, enhanced soil water retention | Capture: low, no<br>Storage: low, no |
| **Ocean alkalinity enhancement** | 1-2 | 40-260 | 1-100 | • For coastal and port cities, artificially increasing alkalinity of seawater | Increased seawater PH and saturation states may impact marine biota. Possible release of nutritive or toxic elements and compounds. Potentially increased emissions of $CO_2$ and dust from mining, transport and deployment operations | Limiting ocean acidification | Capture: low, no<br>Storage: low, no |
| **Artificial ocean fertilisation** | 1-2 | 50-500 | 1-3 | • For coastal and port cities, performing iron or nitrogen and phosphorous additions, or enhanced upwelling | Nutrient redistribution and fundamental alteration of food webs, restructuring of the ecosystem, enhanced oxygen consumption and acidification in deeper waters, potential for decadal-to-millennial-scale return to the atmosphere of nearly all the extra carbon removed | Increased productivity and fisheries, reduced upper ocean acidification | Capture: low, no<br>Storage: low, no |

*Source: JRC analysis (adapted from (Babiker et al., 2022; S. M. Smith et al., 2023)*

While based on a comprehensive survey of the scientific literature, the set of CDRs described in this guidance is not meant to be exhaustive nor static. Innovative solutions are constantly being discovered and tested (e.g., converting biomass to bio-oil injected into geological storage); hence, it is reasonable to expect a wider arena of options in the coming years. Moreover, to be economic and, therefore, to be pursued at adequate scale, most CDR methods require a price for carbon or other incentive system. Future projections of carbon prices may substantially impact the economic feasibility of CDR (The Royal Society, 2018).

The CDR market lingers in an incipient phase expected to go through a rapid development (see **Box 6**), enabled in part by concerted efforts to build institutions and communities for gathering and sharing information (S. M. Smith et al., 2023). The knowledge and know-how that will be generated through the Cities Mission will be instrumental to a faster and safer deployment.

**Box 6.** The present and future of CDRs: key facts (adapted from (S. M. Smith et al., 2023))

Carbon on land is stored in six main reservoirs:

— Almost all current carbon dioxide removal (2 $GtCO_2$/yr, 99%) comes from "conventional" CDRs on land (primarily via afforestation, reforestation and management of existing forests) and a tiny fraction, 0.002 $GtCO_2$/yr (0.1%), results from novel methods (e.g., BioCCS, biochar, DACCS, enhanced weathering). Meeting global climate targets requires rapid growth of both conventional and novel CDRs. Averaging across Paris-relevant scenarios, novel CDR should increase by a factor of 30 by 2030 and by a factor of 1,300 by mid-century. Yet, as of 2023, no country had pledged to scale novel CDR by 2030 as part of their Nationally Determined Contributions, and few countries had published proposals for upscaling novel CDR by 2050.

— Research efforts are skyrocketing. The peer-reviewed scientific literature on CDR is small compared with climate change as a whole but is growing faster. Annual publications are currently doubling every three to four years. Scientific studies on CDR are dominated (about 80%) by biochar, soil carbon sequestration and afforestation/reforestation. Research on biochar is growing faster than that of any other CDR method. BioCCS and DACCS receive comparatively little attention. The science and technology perspective is well covered; however, the social viewpoint (e.g., public acceptance) is very limited.

— Innovation in CDR has expanded substantially in recent years. We see evidence of this in over $4 billion of publicly funded Research, Development and Demonstration (RD&D) projects, a rise in patents and investment in new CDR capacity totalling approximately $200 million from 2020 to 2022.

— CDR is becoming more of a public talking point, although awareness remains relatively low. A growing number of scientific studies on how people perceive CDR indicate public support for research into CDR but raise concerns about deployment at scale. CDR methods that are familiar and often perceived as natural, such as afforestation, are viewed more favourably than others. Discussion of CDR on social media is growing fast, with a trend towards more positive sentiment for all CDR methods except BioCCS.

— Despite growing recognition that CDR needs to be scaled, there is no current global effort to quantify the amount of CDR currently deployed, and whether it is on track to meet the Paris temperature goal.

— According to projections of future global CDR deployment (approximate ranges obtained by fitting both linear and exponential trends to the 2020-2025 deployment data), by 2030 we could see 30.5-208.5 $MtCO_2$ per year of BioCCS deployment, 7-297.5 $MtCO_2$ per year of DACCS deployment, 1.8-65 $MtCO_2$ per year of biochar deployment, and 0.036-0.061 $MtCO_2$ per year of other methods.

— In 2030, global scenarios that limit warming to 2°C or lower indicate additional CDR of 0.96 (0 to 3.4) $GtCO_2$ per year, compared with 2020. By contrast, countries have pledged an additional 0.1 to 0.65

$GtCO_2$ by 2030 in their Nationally Determined Contributions (NDCs) – a range that corresponds to unconditional and conditional NDCs. This suggests that there is already an emerging CDR gap by 2030.

### 5.1.1 Urban carbon removal

The application of CDR methods in cities comes with specific considerations, technical challenges and opportunities, regulatory caveats and advantages, local co-benefits, and engagement avenues for city administrations (**Table 3**). Each city has its own context-specific geographic and jurisdictional particularities, but all have opportunities to act, both within their sphere of control (within jurisdiction) and their sphere of influence (beyond their jurisdiction) (Gevers Deynoot et al., 2024). The choice is among several levers to advance CDR and different roles to play (see **Box 7**).

**Table 3.** Sample of urban CDR options

| CDR methods | Urban implementation options |
|---|---|
| **Biochar** | Produce it from waste biomass available in the city, such as food waste and garden waste, sewage sludge, and urban green residues, and distribute the biochar in public parks and green roofs or use it as an additive in construction materials. |
| **DACCS** | Capture the $CO_2$ from the atmosphere, with stand-alone decentralised modular units or integrated in large building designs and HVAC systems and durably store the carbon in geological reservoirs or mineralised in construction materials used within the city. |
| **Nature-based solutions** | Pursue local afforestation/reforestation projects, restore natural ecosystems within the city, including wetlands, apply soil sequestration techniques to urban farming, build green corridors, and integrate natural materials for more durable storage, such as in wood-based construction and hemp-based construction materials. |
| **Enhanced Rock Weathering** | Distribute silicate rocks or minerals directly in the city on rooftops, urban pathways, or landfill sites, as well as near the built environment in coastal areas or on farmland. |
| **Ex situ mineralisation** | Mineralise atmospheric or biogenic $CO_2$ ex situ in materials such as cement, concrete, and ceramics, or apply it superficially in gravel for roads and parking lots. |
| **Alkalinity Enhancement** | Distribute alkalinity enhancing minerals in water processing facilities such as municipal wastewater and desalination plants, as well as on open water, including rivers and coastal waters. |
| **BioCCS** | Integrate carbon capture technology with waste-to-energy plants and other bioenergy production plants and store the biogenic emissions in geological reservoirs or durable products. |

*Source: JRC analysis.*

**Box 7.** Multilevel governance and residual emissions: levers and roles for city administrations

For cities developing residual emissions strategies, multi-level governance may be particularly important. Many CDR options rely on resources, infrastructure, or regulatory frameworks that extend beyond a city's jurisdiction. Examples include biomass supply chains, geological storage infrastructure, land-based carbon sequestration, or certification systems for monitoring and verifying removals. Multi-level governance influences the regulatory environment enabling or constraining carbon removal deployment, access to funding and incentives, accounting and certification of removals, coordination of infrastructure and supply chains, and partnerships with actors located inside and outside city boundaries. Cities are therefore encouraged to consider governance arrangements as a core component of their residual emissions strategies to strengthen the feasibility and scalability of carbon removal solutions. Both vertical and horizontal multilevel governance matter as removal pathways often rely on value chains that extend beyond city boundaries. For example, biomass used for biochar or BioCCS may originate from surrounding regions, while geological storage sites or land restoration projects are typically located outside urban areas. Coordination with neighbouring municipalities, regional authorities, and private sector actors therefore

becomes essential for developing viable removal systems, share knowledge, pool resources, coordinate infrastructure development, and jointly venture in removal projects.

An enabling multi-level governance system for urban CDR entails well-defined roles and goal alignment:

— At the supranational level, clear standards for carbon removal accounting and certification reduce uncertainty around accounting rules, certification systems, and offer long-term policy support. National governments integrate carbon removal into their climate strategies and establish incentive mechanisms, such as funding programmes, innovation support, or carbon markets.

— Regional authorities coordinate land-use planning and infrastructure development relevant to removal systems, including biomass supply chains or CO2 transport and storage networks.

— Municipal governments implement/promote removal projects, integrate them into climate neutrality plans, and collaborate with local stakeholders. At the same time, cities cooperate horizontally with neighbouring municipalities, research institutions, utilities, and private companies to develop shared projects and value chains. Examples could include regional biochar production systems based on urban organic waste, joint procurement of carbon removal services, or collaborative ecosystem restoration projects in peri-urban areas.

However, in practice, cities often operate in more fragmented governance environments which can limit their ability to develop and implement carbon removal strategies. With a view of gradually creating an enabling environment, cities can:

— **Build coalitions and inter-city collaborations**. Cities can form alliances or join networks to share knowledge, coordinate strategies, and collectively advocate for supportive policy frameworks. Joint initiatives can also help cities achieve economies of scale when procuring or implementing removal solutions.

— **Develop urban–regional partnerships**. Such partnerships can help align urban demand for removals with landscapes capable of providing them. They may involve co-investment in ecosystem restoration, biomass supply agreements, or regional carbon sequestration projects.

— **Implement pilot and demonstration projects.** City-led pilot initiatives can test governance arrangements, demonstrate feasibility, and generate evidence to inform higher-level policy development. Demonstration projects can also help attract investment and build public support for emerging removal approaches.

— **Integrate carbon removal into existing urban systems** (see also **Box 21**). Cities can leverage sectors where they already have operational responsibilities (e.g., waste management, wastewater treatment, district heating, or urban green infrastructure) to implement early removal activities and build local capacity.

Irrespective of its constraints, every city has the agency to act on its residual emissions. The interventions available mainly fall within five categories of action representing the levers available to city administrations: technological, regulatory, urban planning, financial and political-economic levers. Technological levers relate to supporting research, development and innovation efforts, the deployment of demonstration projects and building capacity. Through regulatory and policy levers, cities can create an enabling environment for CDR investment and adoption, creating certainty, offering incentives, and reducing red tape. Urban planning levers enable a city to integrate carbon removal interventions and solutions into spatial planning and the design of low-carbon urban zones. Financial levers allow a city to provide a catalytic funding through a diversity of instruments that draw in private sector investment and make the business case for CDR projects such as public-private partnerships, green bonds and other financial instruments, and carbon pricing mechanisms. Political-economic levers, meanwhile, entail interventions to ensure community buy-in and increase the social licence of CDR such as community engagement, citizen education, innovation summits, and participatory governance models. Figure 3 in (Gevers Deynoot et al., 2025) offers a non-exhaustive list of possible municipal interventions in support of CDR development categorised under each lever.

The municipal toolbox includes many different approaches across the five power levers that local governments can use to support CDR development. As part of a residual emissions strategy, Mission Cities are recommended to identify the tools at their disposal and plan their use in conjunction with ensuring mutual reinforcement and beneficial sequencing. They can be planned according to their function in creating an enabling environment for CDR: driving demand, developing supply, or building societal legitimacy for CDR more generally (Gevers Deynoot et al., 2025).

Depending on its specific constraints, a city can use these levers to a greater or smaller extent, placing them in different roles in relation to the carbon removal stakeholder ecosystem. Knowing which interventions fall within its sphere of control and which fall within the sphere of influence determines the role a city can take, independently and in collaboration with other stakeholders, both within and beyond its individual city boundaries. Based on this operational framework, six key roles for cities emerge when engaging with CDR (Gevers Deynoot et al., 2024):

— **The City as Strategiser**. The city is the main organiser of the city's carbon removal efforts. It sets strategic objectives, guides the actions of local stakeholders, develops clear and robust policy frameworks, and provides financial incentives.

— **The City as Regulator**. The city leverages its powers of regulation, improving the operating environment for CDR developers and investors through specific regulatory interventions, while engaging the general public to ensure citizen buy-in.

— **The City as Service Provider**. The city integrates CDR into its urban planning, treating the carbon sink function of the city as a public service and making it a central feature in the development of its urban and peri-urban environment.

— **The City as Innovator**. The city focusses on supporting the development of a local and collaborative research, development and innovation ecosystem, providing catalytic funding and putting in place the required R&D&I soft infrastructure.

— **The City as Funder**. The city drives demand for carbon removals by introducing meaningful financial incentives, direct procurement, and catalytic investment in pilot projects, limiting funding gaps for developers and reducing risk for private investors.

— **The City as Convener**. The city is an advocate and a critical enabler of the local CDR ecosystem, fostering public debate and awareness raising, while involving citizens in the framing of CDR and any relevant decision-making.

The roles outlined above should be viewed as archetypes, rather than rigid definitions. In reality, cities are likely to embody multiple roles, serving as strategisers in some policy areas and conveners in others, for instance. However, it is essential for cities to identify their primary role or orientation, as this will shape their overall approach to promoting carbon removal within their boundaries and beyond. By determining their core role, cities can inform their choice of tools and strategies, ultimately guiding their efforts to advance carbon removal.

Despite being crucial actors of change and places for project deployment, cities have so far received limited attention from both the research community and practitioners around CDR. Significant experience has been built over time with the introduction of nature-based solutions (NBS) in urban settings, though often not for the purpose of realising negative emissions and lacking dedicated measurement, reporting, and verification of the climate impact realised. Nevertheless, the global potential for urban CDR has been assessed at over 1 $GtCO_2$/yr by 2050, representing a significant opportunity for climate change mitigation (Rodriguez Mendez et al., 2024). This may be a conservative estimate given that the assessment focusses on urban vegetation, soils and buildings, as well as decentralised DAC in indoor environments, yet several CDR methods suitable for urban application are not included such as alkalinity enhancement, ex-situ mineralisation with DAC or

captured biogenic emissions, and enhanced rock weathering. Meanwhile, a first-ever city-level assessment of the CDR potential in and around the Mission City of Amsterdam found a potential for BioCCS pathways (waste-to-energy, biogas production, and wastewater treatment) to remove approximately 1 $MtCO_2$/yr by 2050. That potential is likely higher when considering other CDR methods (South Pole & Bellona, 2022). More details are provided below.

**City in the spotlight: Amsterdam (The Netherlands)**

In 2022, the Mission City of Amsterdam commissioned a world-first high-level assessment of the carbon removal potential in and around the Amsterdam Metropolitan Area and the North Sea Canal Area (NSCA) (South Pole & Bellona, 2022). The study was motivated by a desire from the city to explore opportunities for accelerating climate change mitigation in the period up to 2030. BioCCS was identified as having the greatest potential for carbon removal in the short-to-medium term. The authors interviewed city officials and relevant companies along the BioCCS chain (both inside and outside the jurisdictional boundary) including: i) biogenic $CO_2$ emitters; ii) $CO_2$ transport providers; and iii) $CO_2$ storage providers, both in the form of geological storage and carbon mineralisation in durable products. The study identified a cumulative potential for BioCCS of ~900 $ktCO_2$/yr in Amsterdam and the NSCA. This is expected to be a conservative estimate, given that not all the existing emitters of biogenic carbon in the region were mapped.

The three most important sources of biogenic emissions identified were:

— Combustion of biogenic waste. The city's waste incineration plant AEB combusts waste or biomass for steam, heat and electricity. At the time of the writing, AEB generated ~1.1 $MtCO_2$/yr, of which ~60% of biogenic origin, equalling a potential to remove ~450 $ktCO_2$/yr.
— Biofuel production from existing and planned facilities for the production of biogas, biomethane or biomethanol through the fermentation of biomass. A potential of at least ~216 $ktCO_2$/yr was identified.
— Wastewater treatment. The city's water utility company Waternet operates the largest wastewater treatment plant in the Amsterdam port area. A potential of at least ~85 $ktCO_2$/yr was identified.

Waste incinerators and bioenergy plants frequently represent the largest source of biogenic $CO_2$ emissions in an urban area. However, storing biogenic emissions requires adequate transport and storage infrastructure which may not always be readily available. Depending on the volume of emissions, a city can support the logistics of BioCCS supply chains by taking into account different modes of transport, repurposing existing pipeline infrastructure, and connecting up with industrial carbon capture and storage hubs. Common barriers that may hinder the development and deployment of BioCCS are associated with regulation (lengthy permitting and end-of-waste status), policy (absence of supportive targets and legislation), finance (insufficient incentives), infrastructure (lack of readily accessible transport and storage infrastructure), and public awareness and acceptance. A city can actively reduce these barriers. For example, a city can reform its permitting processes to reduce costs, introduce CDR-specific policy and targets to foster demand, fund infrastructure development and provide financial incentives to make the business case, and engage the general public around showcase projects to increase public awareness and buy-in.

**Natural carbon sinks** in cities are expected to cover only a limited share of residual emissions as the $CO_2$ sequestered per unit of land area and the land available for e.g., extensive afforestation programmes are typically very low. Further, many natural carbon sinks suffer reversal risk. While capable of storing carbon for millennia, challenging conditions such as changing political priorities, economic pressures, fire, disease and risks associated with climate change itself, all conspire to increase the risk that the stored carbon will be re-emitted in the near-to-medium term (M. Allen et al., 2020). Ensuring permanent sequestration requires caution and appropriate safeguards, to make natural carbon sinks a low-risk option over the long term. However, natural carbon sinks deliver a number of direct and indirect benefits relevant to both carbon sequestration and emissions reduction that warrant their inclusion and maximisation in climate mitigation action plans. A first

estimation around common nature-based solutions is provided in (Pan et al., 2023). Further, the support to restoration, protection, and enhancement of a wide range of natural and semi-natural ecosystems shall be rapidly scaled up irrespective of the carbon benefit it may or may not provide, as it is attached to invaluable co-benefits for a sustainable life on Earth. Consequently, any residual emissions strategy that neglects the role of natural carbon sinks would be incomplete in view of delivering holistic climate planning. Such an approach should only be considered if there is a strong and well-justified reason for ruling out nature-based solutions (NBS). Cities may consult a 2020 publication by the Directorate-General for Research and Innovation (Commission et al., 2020) that condenses expert reports around the use of NBS in EU research and innovation projects through the lens of carbon capture and sequestration, climate adaptation, biodiversity, water quality, air quality, microclimate, sustainable communities, innovative governance and business models, and market challenges and solutions. The analysis covers co-benefits and cost-effectiveness of NBS and includes policy recommendations that might guide the definition of the optimal residual emissions strategy. On the other hand, trade-offs should not be underestimated, especially when food security and the needs of rural, local, and indigenous communities are at stake (see, for instance, **Box 8**).

**Box 8.** Carbon farming: opportunities and limitations

Individual farmers, land and forest owners or forest managers can be encouraged to store more carbon, prioritising ecosystem-based approaches and biodiversity-friendly practices, such as close-to-nature forestry practices, set-aside areas, the restoration of forest carbon stocks, the expansion of agroforestry coverage, soil carbon sequestration and restoration of wetlands as well as other innovative solutions (European Parliament and Council, 2023b). This can be nurtured via targeted policies and incentives. The 2021 Commission's Communication on Sustainable Carbon Cycles (European Commission, 2021f) stresses the importance of carbon farming as a green business model that rewards land managers and incentivises the take-up of improved land management practices, resulting in the increase of carbon sequestration in living biomass, dead organic matter, and soils. This is achieved by enhancing carbon capture and/or reducing the release of carbon into the atmosphere.

Examples of carbon farming practices include (European Parliament and Council, 2024b):

— Afforestation, reforestation and sustainable forest management activities that respect ecological principles, are favourable to biodiversity, and adapt forests to climate change.

— Agroforestry and other forms of mixed farming, such as combining woody vegetation (trees or shrubs) with crop and/or animal production systems on the same land.

— Use of catch crops, cover crops, conservation tillage and increasing landscape features to protect soils, reduce soil loss from erosion and enhance soil organic carbon on degraded arable land.

— Improved grassland management, e.g., convert arable land for fodder crops to permanent grassland.

— Restoration of peatlands and wetlands that reduces oxidation of the existing carbon stock and increases the potential for carbon sequestration.

When dealing with carbon farming, cities should promote food security, the protection and the restauration of biodiversity and ecosystems, and avoid that land is acquired for speculative purposes resulting in negative effects on rural communities. Cities should also design their residual emissions strategy respecting the rights of local communities and indigenous people affected by associated activities, where relevant. Cities should prioritise activities that have the largest potential to provide positive co-benefits for biodiversity, as well as consider the long-term forest structure, the long-term stability of carbon pools, ecosystem health, resilience and risk of natural disturbances. Practices that produce harmful effects on biodiversity, such as forest monocultures, should not be considered in the framework of the Cities Mission (see also **Box 32** and **Section 6.3**).

Specifically in cities, **biochar** applications have large synergies with different urban vegetation types: biochar can be used in street-tree pits for stormwater management (Azzi et al., 2022), applications in landscaping soils such as residential gardens, urban forests and parks (Ariluoma et al., 2021), and additions to green roof substrates, where biochar is an excellent material due to weight being a common limiting factor (Kinnunen et al., 2022). Another application – comparatively underexplored but well suited to urban environments - is the use of biochar in the construction sector (Y. Zhang et al., 2022). Serving as a mineral filler or cement substitute, it helps regulate moisture and $CO_2$ diffusion in cementitious composites, with the stored carbon remaining stable even in waste concrete. Its use in construction materials is mainly limited by potential impacts on mechanical properties. Incorporating biochar into construction materials contributes to make it possible to conceive of buildings as carbon sinks (Osman et al., 2024).

Potential synergies between the carbon sequestration capacity of forests and the associated carbon storage capacity of dense mid-rise cities built from **engineered timber** offer the opportunity to construct carbon sinks deployed at large scale (Churkina et al., 2020). Harvesting pressures on forests can be reduced through the reuse and recycling of wooden components from dismantled timber buildings. Policies and practices promoting design for disassembly and material reuse will increase their durability (IPCC Working Group III, 2022a). Transitioning to biomass-based building materials, implemented through the adoption of engineered structural timber products and assemblies, will succeed as a mitigation strategy only if working forests are managed and harvested sustainably (Churkina et al., 2020). Since future urban growth and the construction of timber cities may lead to increased timber demand in regions with low forest cover, it is necessary to systematically analyse timber demand, supply, trade, and potential competition for agricultural land in different regions (Pomponi et al., 2020). Robust forest and urban land governance, as well as accurate carbon accounting and MRV frameworks, will be necessary to enable a responsible large-scale adoption of biomass-based urban construction materials and techniques (IPCC Working Group III, 2022a).

Buildings in urban areas could utilise **direct air capture (DAC)** technologies to capture $CO_2$ from high concentration environments like city centres and indoor spaces, possibly leveraging existing heating, ventilation, and air conditioning (HVAC) systems to enhance energy efficiency (Tian et al., 2023). The captured $CO_2$ would have to be appropriately processed, transported, and stored in geological formations to produce permanent removals, with energy requirements and feasibility varying based on specific applications and contexts. Future demand for non-fossil carbon from industries may help reduce the costs of implementing decentralised DAC units in the built environment by increasing the price of carbon (Baus & Nehr, 2022); however, the convenience of decentralised DACCS as an option may remain limited by other factors, such as the availability and accessibility of renewable energy sources, the need for long-distance transportation of liquefied CO2, and the significant energy requirements of the DAC infrastructure itself. Large buildings, such as airports and universities, may be better suited for incorporating DAC modules due to logistical considerations, though challenges remain in specifying transport modes and system components. Estimates suggest significant $CO_2$ capture potential from decentralised DAC in commercial buildings globally, but uncertainties around feasibility, costs, and storage solutions highlight the need for further research and development (Rodriguez Mendez et al., 2024).

**Ex situ mineralisation** of carbon captured from ambient air or from biogenic sources holds significant potential for reducing the embodied carbon of the built environment and transform buildings into carbon sinks. For projects to be viable, researchers have identified a number of preconditions, including that the resulting products are used as a supplementary material in cement

blends in the construction industry and that the project can access climate finance opportunities, specifically from the voluntary or compliance carbon markets. Mineral transport and composition are other decisive factors. Researchers have found that feedstock minerals shall be available relatively close (<~450 km without ship transport or 2000 km with ship transport) and the shares of silica in the produced cement shall not be too high (Strunge et al., 2022). Feedstocks with a likely close proximity include industrial by-products such as construction and demolition waste rather than geologically derived feedstocks.

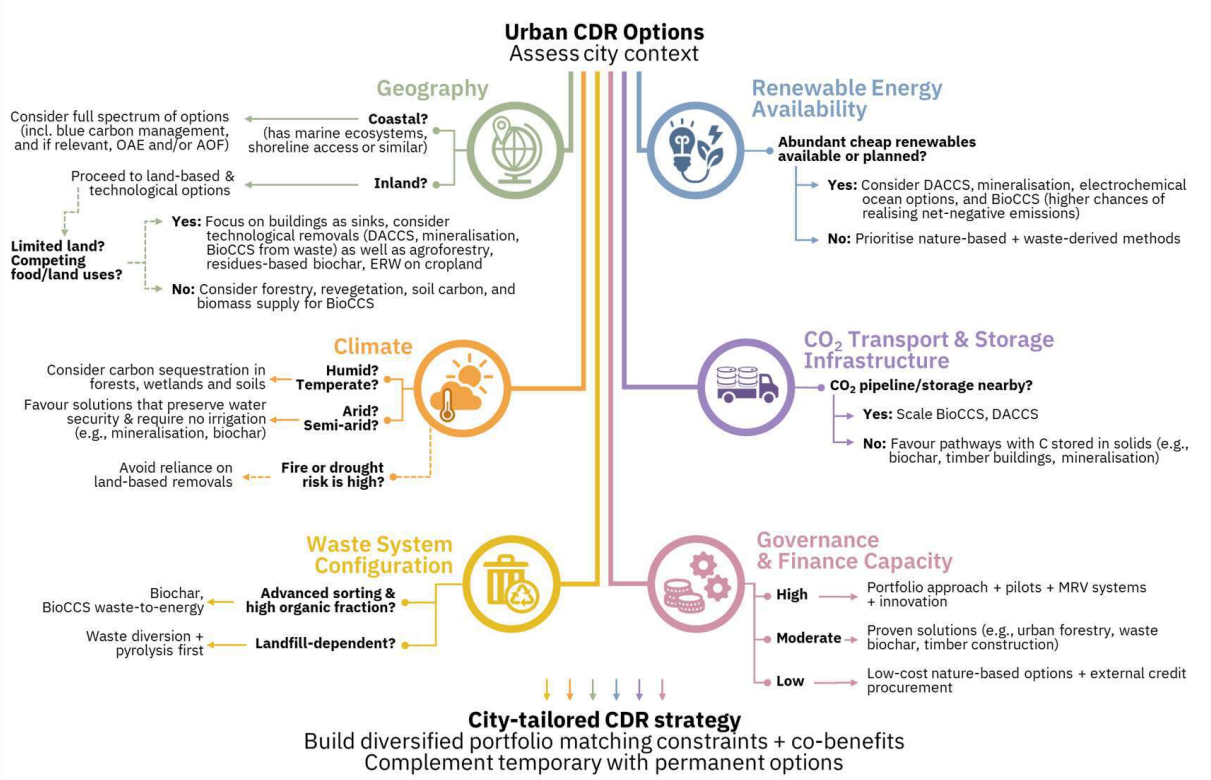
**Enhanced Rock Weathering (ERW)** as a CDR method has relevant applications in urban settings and can be integrated into urban greening efforts. Research and data from deployment remains limited, but the potential of ERW in urban farming has been positively assessed as a means to increase the sequestration of inorganic carbon within the soil (Haque et al., 2021). Despite potential climate benefits, the deployment of ERW within cities comes with challenges, particularly around the need for a consistent supply of crushed minerals, high cost of transportation to a relatively high number of small areas for deployment, and need for specialised large-size equipment potentially obstructing transport, construction or other urban activities.

**Wastewater Alkalinity Enhancement (WAE)** is an early-stage application of Ocean Alkalinity Enhancement (see **Annex 2**) that has relevance to cities with wastewater processing plants or desalination plants within or near the city boundary. By increasing alkalinity, wastewater can convert more of the dissolved $CO_2$ into bicarbonate and carbonate ions. Not only can this result in a reduction of emissions from the plant, but it can also potentially realise negative emissions. Though environmental impacts shall be assessed, including pH values, the deployment potential is significant, given the global network of wastewater treatment plants (a source of $CO_2$ due to the oxidation of organic matter). Integrating alkalinity addition into treatment processes may reduce in-plant $CO_2$ emissions and increase downstream $CO_2$ uptake (M. Li et al., 2025).

The estimated potential contributions toward carbon storage of different CDR options are still plagued by patchy science and a relative lack of demonstration projects for most methods within urban settings, as well as limited data on costs, potential adverse effects, social legitimacy, geographical and climatic variability, methodological discrepancies, lack of connectivity between co-benefits and market-based mechanisms or regulatory instruments, and lack of governance frameworks (Rodriguez Mendez et al., 2024).

Cities wishing to pursue a portfolio of CDR methods to compensate for residual emissions are advised to carefully analyse their context (see **Figure 4**) and develop strong governance principles, integrated plans and frameworks that involve direct and indirect interventions from decision-makers, while ensuring direct engagement from communities affected by a given project. This is crucial to secure the social legitimacy needed for projects to succeed in responsibly removing $CO_2$ and to foster a just transition (Nawaz & Satterfield, 2024). Demonstration projects are inherently social and needed to show citizens that a given solution has worked well for communities like theirs (Buck et al., 2024).

**Figure 4.** Decision tree for identifying urban carbon dioxide removal strategies tailored to a city's context. OAE: ocean alkalinity enhancement; AOF: artificial ocean fertilisation.




*Source: JRC analysis. Images adapted from Noun Project ("renewable energy" from Andre Buand) and Microsoft PowerPoint (all other icons).*

**Cities in the spotlight: Warsaw, Wroclaw (Poland), Angers Loire Métropole, Grenoble-Alpes Métropole (France), Glasgow (United Kingdom), Izmir (Türkiye), Münster (Germany), Athens (Greece), Oslo, Trondheim (Norway), Riga (Latvia), and Zagreb (Croatia)**

The governance of carbon sequestration in Mission Cities involves a range of institutional, regulatory and planning instruments, financial instruments, participative governance mechanisms, and capacity-building initiatives.

Warsaw has established a range of policies and programmes to support natural sinks (Warsaw, 2025). The **Environmental Programme** aims to protect the surface of the earth and water from pollution and degradation, while the **Municipal Revitalisation Programme** focusses on eliminating threats to the natural environment and building resilience to climate change risks. The city also has a number of community and citizen initiatives, such as the **Million Trees for Warsaw programme**, which encourages residents to suggest planting sites using an app. Furthermore, Warsaw has introduced **regulations** and **incentives** to support green initiatives, including the **Warsaw Greenery Board**, which cares for and finances the maintenance and development of green spaces in the city, and the **Green Fund**, which provides financial support for green projects. The city's efforts to promote green infrastructure are further supported by its **Municipal land buy-back programme**, which allows the city to acquire land for green spaces. The **Warsaw Climate Change Adaptation Guidebook** provides education and support for residents, cooperatives, and businesses to remove concrete surfaces, plant greenery, and set up small-scale retention facilities. The city also promotes community involvement through initiatives such as the **Warsaw Booster acceleration programme, Urban Living Lab, and Participatory Budgeting**, which support the development of innovative solutions in the sector. Finally, Warsaw develops accessible green

spaces close to where people live and engages residents and the private sector in monitoring and protecting nature-valuable areas through citizen science activities, provision of tools, and family allotments as biodiversity sites.

Similarly, Wroclaw is implementing a range of greening programmes and initiatives, including the "**Green Lungs of Wroclaw**" and "**Park on every estate**", while the **Stormwater Management Strategy** and programmes such as "**I like rain**" and "**Catch the rain**" stimulate unsealing of concreted surfaces, retention of rainwater, and prevention of flooding (Wroclaw, 2025). The city is also introducing **provisions in local plans** to protect and develop blue-green infrastructure, and providing **funds in the city budget** for the purchase of land with natural value to protect it from urban pressure. The city promotes innovative initiatives, such as the "**GROWin WROclaw**" programme, which involves planting trees with newborns and young children as patrons, the "**Green Culture**" municipal programme, or the "**Green Patronage**" programme, which encourages residents and businesses to sponsor green solutions in the city, and the "**WROchef**" competition, which promotes plant-based diets among elementary school children by partnering with restaurant chefs and finalists of MasterChef to reward sustainable choices. Also, the "**Wroclaw Magnolia**" competition, which aims to promote innovative projects and solutions that have a positive impact on air quality and biodiversity, and the "**Saturday with Green Wroclaw**" family picnic, which introduces residents to the city's sustainability activities, are notable examples of the city's commitment to engaging citizens and stakeholders in creative and inclusive ways. Wroclaw is further promoting community involvement and social innovation through initiatives such as the "**Wroclaw Participatory Budget**" and the "**Civil Panel**", which allow residents to contribute to the development of a sustainable and resilient urban environment.

Angers Loire Métropole promotes a variety of initiatives and instruments to support its carbon sequestration efforts (Angers Loire Métropole, 2025). The métropole is committed to gradually reducing the rate at which land is artificially developed, with the aim of achieving **zero net artificialisation** by 2050. This objective is being incorporated into urban planning documents and new development projects, including large-scale mixed projects, housing, business parks, and urban renewal projects. Furthermore, the métropole has set an **objective to triple carbon stocks by 2050** and is strengthening its **biodiversity plan**, which includes discovering, raising awareness, and training to improve collective action, sharing and pooling to improve knowledge, preserving and restoring to protect the natural heritage, innovating and experimenting to meet new challenges. The métropole is also implementing the **Angevins landscape master plan** and the **Urban Nature Plan**, which aim to strengthen the area's landscape identity, sustainable design and management, and tree heritage. The métropole is also engaging in **partnerships**, agroforestry transitions, and **community-led projects**, such as urban gardens, to promote cross-sectoral alignment. A **participatory approach** is in place, with stakeholder collaboration and localised action, as evidenced by the Ecological Transition Conference and citizens' roadmap.

Grenoble-Alpes Métropole's **inter-territorial forestry strategy**, launched in 2019, aims to encourage local use of wood and develop carbon sequestration, while the **Chartreuse forest and wood label** promotes sustainable management of the resource, the environment, and carbon sequestration (Grenoble-Alpes Métropole, 2025). The **Regional Wetland Restoration Plan** and the **Agricultural Strategy** also include actions to maintain and strengthen carbon sequestration in wetlands and soils. The **Canopy Plan**, launched in 2022, aims to increase the number of trees in urban areas and contribute to carbon sequestration, with a goal of reaching 30% canopy cover by 2030 and 40% by 2050. The use of timber in construction is encouraged through the decarbonisation objectives for new buildings set out in the **Land Use Regulation Plan**. Furthermore, the métropole's commitment to collaborative climate action is evident through social innovation actions, like the **Citizens' Convention for the Climate**, and its **participation in EU-funded projects**, such as Food Trails, CityZen, and Climaborough.

Glasgow fosters engagement with all local and regional stakeholders, including landowners, to ensure that its peatlands are restored and protected (Glasgow, 2025). The city is also developing an **Urban Woodland**

**Strategy**, which will look at how trees deliver a range of benefits, including carbon capture, development, leisure, heat reduction, water management, food, biodiversity, and construction. An **environmental digital model** is being developed alongside this strategy. The city is also accelerating the implementation of the **Glasgow and Clyde Valley Blueprint for a Green Network**, which will create green and biodiversity corridors in the city by improving open space provision and increasing tree cover. The city's initiatives, such as the **Glasgow Clyde Valley Green Network Partnership, Sustainable Glasgow Partnership, and Climate Ready Clyde**, create an enabling environment for the deployment of nature-based solutions and support the development of actions in the agriculture, forestry, and other land use sector. These partnerships and collaborations facilitate the development of regional approaches to increasing carbon sequestration and biodiversity gains, while also promoting the **restoration of peatland, wetland, woodland, and grassland**. The city is also developing a **Peat Free Procurement Strategy**, which will require 100% peat-free products for specific projects, such as nursery and bedding plants. The city will engage with procurement units and suppliers to establish the best alternative products available.

Izmir proposes a comprehensive approach to land use for carbon sequestration, addressing urban greening, sustainable agriculture, and forestry while promoting sustainable land use and agriculture practices (Izmir, 2024). Its **low-carbon farming strategy** focusses on soil and grassland management along with nutrient and livestock management to optimise carbon sequestration, precision agriculture and renewables to maximise the net negative emissions effect. The strategy also insists on **community engagement and education** with the formation of farmer cooperatives, farmer advisory groups, and awareness campaigns to help educate farmers on climate-smart agriculture practices and promote the adoption of sustainable methods. Finally, the establishment of a **dedicated department** for monitoring and enforcing climate-smart practices in agriculture ensures that the strategy's goals are tracked. The city also looks at a multipurpose agenda; for instance, the creation of **Living Parks and İzmir Heritage Routes** is meant to protect biodiversity and promote ecosystem services.

Similarly, Münster's approach to carbon removal governance emphasises **stakeholder and citizen involvement**, raising awareness through education and collaboration with regional policies (Münster, 2024). The city's **Agricultural Officer** plays a key role in fostering communication with local farmers and integrating agricultural perspectives into climate protection projects. A comprehensive nine-month soil practitioner course, jointly organised with agricultural associations, educates farmers on carbon storage, soil protection, and water retention capacity. Other educational initiatives, such as **Climate walks**, aim to raise awareness and stimulate action among citizens, while also promoting synergies with regional policies.

Athens has established an **extensive plan** for land expropriation, upgrading of hills and groves, and reinforcement and restoration of streams, and has set **ambitious goals for tree planting** (Athens, 2025). The city is also **increasing funding sources** for green infrastructure, **hiring new staff**, and providing **training** on nature-based solutions for municipality departments, citizens, and other stakeholders. The city's approach to governance is also characterised by a strong focus on social equity, with initiatives such as the **GreenInCities project**, which aims to address urban inequality by improving the microclimate, sustainable mobility, and accessible infrastructure for all ages and social groups. The city has also established a **new regulation** on green infrastructure, strengthening its commitment to a sustainable and green future. Additionally, the city has implemented an Integrated Framework of Actions for the digital upgrade, development, and modernisation of the infrastructure and equipment of the **Department of Greenery and Urban Wildlife**.

Oslo's land-use policies promote **densification** and **multi-aged and mixed forests** through selective harvesting and natural rejuvenation (Oslo, 2025). The **Agency for Planning and Building Services** is revising the regulations concerning the **blue-green factor**, a tool used to safeguard blue-green structure in construction projects. The city is also revising the land-use section of the municipal master plan, laying foundations for Oslo to become a climate-resilient city. Further, an assessment will be made as to how, through the stipulation of requirements in **procurements**, the city can grow demand for slow-growing and

**sustainable timber** of larger dimensions, which in turn can contribute to durable, high-quality timber products, and with an increase in the proportion of timber which is utilised.

Trondheim's governance structure plays a pivotal role in supporting carbon sequestration efforts (Trondheim, 2025). The city has implemented **area-neutral regulations**, which ensure that any new development or land use does not come at the expense of natural carbon sinks. Additionally, the city has introduced **incentives** for landowners to restore and protect natural habitats, making the real cost of reducing nature and agricultural land visible in the early planning stages of projects. The city provides **funding** for nature restoration, both from the public and private sectors, and has established **partnerships with NGOs and agricultural organisations** to promote sustainable land use practices. The city also **engages its citizens** in the decision-making process, raising awareness about the importance of viable nature and farmlands through **information campaigns and participation projects**. For example, Trondheim has launched urban farming initiatives and citizen science mapping projects, which not only increase community involvement but also provide valuable data for monitoring and evaluating the city's carbon sequestration efforts. Furthermore, the city uses its **public procurement** power to promote local food production, supporting farmers who adopt sustainable practices and reducing the city's reliance on industrial agriculture.

Riga's development of a **Street Greenery Renovation Plan** and an **Urban Environment Greening Plan** 2027-2031, as part of the **EU-funded project LIFE LATESTadapt**, aims to enhance the city's green infrastructure and promote sustainable urban development (Riga, 2025). The city is also developing a **Biodiversity Strategy**, which will further support the creation of an enabling environment for carbon sequestration. The city is prioritising plants that have low resource demands and are resilient to the impact of climate change and is installing beehives on the roofs of municipal buildings. Additionally, the city is developing a **regulatory framework** to increase $CO_2$ sequestration and the implementation of nature-based solutions, including the revision of land use and development regulations, the development of a 'green factor' that takes greening and nature-based solutions into account, and the amendment of the **Protection Zone Law** to promote the greening of streets. The city is also providing **information, education, awareness-raising, and engagement opportunities** for local residents and businesses, including the development of guidelines for their participation in the greening of urban areas, and the provision of support mechanisms.

Zagreb explicitly embeds residual emissions into the **Green General Urban Development Plan, the Green Deal Building Design Standards**, and the city's governance architecture (Zagreb, 2025). This ensures that carbon sinks protection and enhancement is spatially planned, technically standardised, and institutionally anchored. The city's **Green Deal Design Guidelines** go beyond national minimum standards, requiring mandatory climate proofing of all new projects, integration of on-site carbon sinks, circular construction and bio-based materials, and Do No Significant Harm (DNSH) and EU taxonomy alignment. The city's **Climate Cockpit** governs residuals, with cross-departmental ownership and public transparency, ensuring that residuals and removals are tracked on a **public dashboard** alongside emissions reductions. Zagreb's **financing strategy** for residuals is also well-established, with mainstream investment, including European Investment Bank (EIB) framework loans, Cohesion Policy 2021–2027 and Recover and Resilience Facility (RRF) funds, and private capital and ESCO models, mobilised for bio-based construction and materials banks. The city also facilitates the uptake of **Common Agricultural Policy (CAP) eco-schemes** and carbon farming pilots by farmers and cooperatives.

## 5.2 Out-of-boundary carbon removal credits

Another way to compensate for residual emissions is to offset emissions by removing emissions somewhere else. This can be done through the purchasing of carbon credits generated from projects outside the geographic boundary (see **Section 6.2**).

A carbon credit is a tradable environmental certificate that represents a metric ton of carbon dioxide-equivalent ($CO_2$-eq) that is avoided, reduced or removed. To generate carbon credits, a project shall be certified through rigorous standards and verified by independent third-party auditors. Carbon credits are issued to a registry and remain tradable until they are retired, signifying that they have been used for climate offsetting or climate contributions. Permanently retiring the credit in a registry ensures that it cannot be reused and guarantees its unique contribution to climate action (see also **Box 9**). Beyond their climate impact, these projects often deliver additional co-benefits, like empowering communities, protecting biodiversity or improving public health.

Carbon credits can be broadly classified into two categories, a distinction that directly derives from the type of project activities. Reduction and avoidance projects focus on curbing, preventing or avoiding the release of greenhouse gas emissions that would have otherwise occurred; they generate carbon reduction or avoidance credits. Removal projects are designed to actively capture and store GHG emissions that are already in the atmosphere and generate carbon removal credits. For a more granular breakdown of this classification and outline of associated risks and benefits, see **Box 10**.

In the Cities Mission, **only verified and retired carbon credits associated with carbon removal activities can be used to compensate for residual GHG emissions** occurring within the boundary. Carbon credits originating from projects which reduce or avoid future $CO_2$ emissions, such as renewable energy or forest conservation projects, are not eligible for residual emissions compensation in the Cities Mission. This aligns with the principle that the only way to achieve and maintain net-zero, and ensure alignment with the Paris Agreement, is to compensate for any residual emissions with durable removals (Axelsson et al., 2024; Cullenward et al., 2023). Any credits used to compensate for residual emissions increasingly need to come from activities that store carbon with a low risk of re-release into the atmosphere.

Knowing where to start when establishing a carbon credit portfolio can be challenging for city administrators who are not traditional carbon market operators. Questions around the quality of the projects, how to navigate the rapidly evolving nature of the carbon markets' governance, and the differences between avoidance, reduction and removal credits need to be addressed to equip Mission Cities with the tools to define their own path when considering the use of carbon credits (see **Box 10**).

This section will describe under which conditions Mission Cities can use carbon credits as part of their compensation strategy and will lay down the knowledge they need for a high integrity residual emissions strategy.

**Box 9.** The lifecycle of carbon credits: issued, sold, retired

The period of time during which a carbon credit project generates verifiable and/or certifiable carbon credits is known as crediting period. After the end of the crediting period, the project can be re-evaluated against current standards for renewal, otherwise the project will cease to produce carbon credits (C40, 2019).

Based on the time of issuance, we distinguish:

— **Ex-post carbon credits**, issued once the carbon benefit has materialised. For example, the credit is issued when the forest has successfully grown and has removed the planned amount of carbon. Consequently, there are fewer risks for the buyer and the credit retirement can happen immediately as soon as it is sold.

— **Ex-ante carbon credits**, issued before the carbon benefit takes place, based on the expected outcome of the project in the future. Using the same example, the credit is issued when the seedlings are planted and started to grow. The benefit is realised when the trees are mature. The buyer receives the carbon certificate, but the credit is only retired once the benefit has been realised. This brings greater risks for the buyer.

— **Pre-purchased carbon credits**, sold before they are formally issued. It represents a commitment from the early stage project developer that it will issue credits once the project is ready. In the forest example, the credits are sold when the project design is ready, but the seedlings have yet to be planted. This comes with even greater risks.

Ex ante and pre-purchased carbon credits are a more common market phenomenon when dealing with carbon removal projects that are highly innovative and have the potential for large, scalable, and highly durable carbon storage. This includes BioCCS and DACCS projects. To reduce the risks associated with buying such credits, buyers can rely on carbon credit ratings throughout the project lifecycle, from design, to implementation, to pre-issuance.

Cities involved in the Mission are advised to build a portfolio of credits that prioritises ex-post carbon credits as a foundation, accompanied with ex-ante or even pre-purchased credits from projects with expected benefits that start to materialise before 2030. This preference ensures that their status of climate neutrality can be conclusively confirmed when the 2030 inventory is finalised and would be in line with the CRCF (European Parliament and Council, 2024b). The CRCF requires that certified units are issued solely after a re-certification audit verifies the generated net benefit. While initial estimates of expected benefits are part of the certification audit, these estimates primarily inform the activity plan for certification, not the issuance of units. This approach helps safeguard the integrity of offsetting claims by avoiding premature crediting, reducing the risk of reversals, and mitigating concerns around greenwashing.

**Box 10.** Non-removal credits and their role in and beyond the net-zero journey

Common examples of non-removal carbon credit projects include (C40, 2019):

— Renewable energy (hydro, solar, tidal, wind, biomass, geothermal) and/or energy efficiency (fuel switching, energy efficiency supply/demand side, transport modal shift).

— Household devices and community-based projects (clean and energy efficient cookstoves, water filters, household biogas, home solar systems).

— Agriculture, Forestry and Other Land Use (avoided deforestation, forest management, changes in agricultural management, soil carbon enhancement).

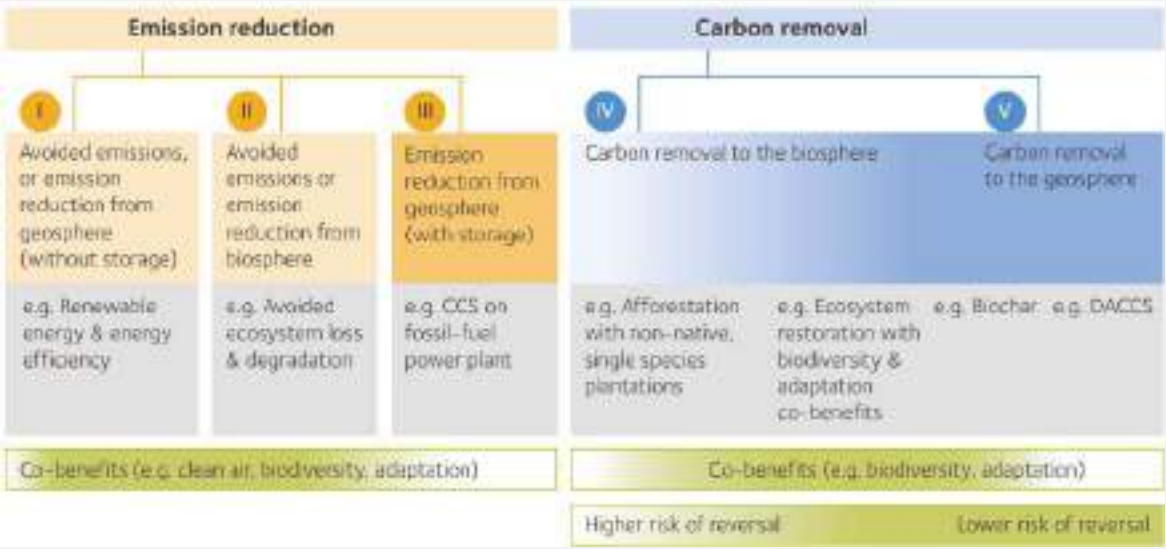
— Changes in organic waste management (composting, landfill gas, refuse derived fuel, waste-to-energy, anaerobic digestion).

— Electric vehicles (EVs) (2-4 wheeler EVs, e-Buses, e-Trucks, EV charging stations)

— Circular economy activities as an avoidance measure (reducing emissions both from end use waste and upstream emissions from transport).

Going deeper into the types of carbon credits, the simplified classification scheme proposed by the University of Oxford (Axelsson et al., 2024) and displayed in **Figure 5** shows five different project classifications which distinguish between emission reductions and carbon removals, highlighting where carbon is removed from the atmosphere, how it is stored (in the biosphere or geosphere) and the risks and benefits associated with these different approaches.

**Figure 5**. Simplified classification scheme of the five types of carbon offset. The shading of colours from light to dark pertain to the durability of storage. The risk of reversal of storage types and co-benefits are illustrated as gradient bars below the project types.




*Source : Adapted with permission from (Axelsson et al., 2024)*

Achieving the net-zero status requires that any emissions which cannot be eliminated are removed from the atmosphere and stored with low risk of reversal. Activities that do not result in actual $CO_2$ removal are, by definition - conceptually, physically, and procedurally - not eligible as part of a residual emissions strategy, even if they are supported by existing crediting programmes and mechanisms (see also the like-for-like principle in **Section 5**).

While reduction and avoidance credits cannot be used to compensate for residual emissions in a net-zero claim, they remain a way to deliver measurable climate impact. Cities should not stall their action as they can still make a valuable contribution to global climate change mitigation by investing in other types of crediting activities. While these efforts do not support a net-zero claim, the city's continued climate action and investment will be acknowledged as a meaningful contribution to broader mitigation goals.

### 5.2.1 Carbon markets and carbon crediting programmes

There are two primary types of carbon markets: compliance and voluntary. Compliance markets are mandatory, established and regulated by national, regional, or international governmental bodies, and tend to operate under a cap-and-trade system. The EU Emissions Trading System (ETS) and UK ETS are examples of compliance carbon markets. Governments set a cap on total emissions, issue allowances to regulated entities, and allow entities to trade allowances if they emit less than their allotted amount. There are other national and sub-national compliance carbon markets in the world, as well as sector-specific compliance markets, such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) where airlines must surrender carbon credits to cover any emissions exceeding their baseline, ensuring carbon-neutral growth for the sector. Compliance markets also include international cooperative approaches, such as Article 6 of the Paris Agreement (see **Box 11**), which allows governments to trade mitigation outcomes to achieve their Nationally Determined Contributions (NDCs). In these systems, carbon credits or allowances facilitate the sharing of mitigation efforts toward a common goal.

Under the Cities Mission, any large-scale energy generation or industrial facilities located within the city boundary which are registered under the EU ETS may be exempt from the climate neutrality target on the basis that municipalities have very limited influence over their operation and there is a dedicated EU process to reduce emissions from these sources; it is optional for cities to include them if specific measures are foreseen (European Commission, 2021g). Where ETS facilities are included, and accordingly, their emissions reflected in the inventory, cities should transparently report on the associated credits as well, if any. The Implementing Regulation (EU) 2018/2066 (European Commission, 2018b) sets out detailed rules on monitoring and reporting of GHG emissions under the EU ETS. For emissions covered by other types of emissions trading schemes, the underlying trading systems shall come with rigorous monitoring and verification protocols, transparent tracking and reporting of units, and stringent caps to be eligible for emissions compensation.

In contrast to compliance markets, the Voluntary Carbon Market (VCM) allows corporates, organisations, as well as individuals to voluntarily purchase and retire carbon credits. Buyers typically engage in the VCM to i) achieve net-zero commitments or climate strategies, ii) support social responsibility efforts in response to stakeholder demand, or iii) prepare for future mandatory carbon pricing by building internal capacity in procurement and carbon accounting. The VCM is a complex ecosystem connecting climate action projects with end buyers. Multiple actors participate in the market to execute transactions while ensuring effectiveness, integrity, and alignment with climate goals. The quality of credits in the VCM has been an issue of debate in recent years as a result of research showing major deficiencies with carbon projects, particularly those related to forestry. This has engendered additional quality assurance mechanisms to improve the workings of the carbon crediting programmes certifying and issuing the credits (see also **Box 12**).

The VCM is based on self-regulation, although governments increasingly regulate the claims associated with the use of carbon credits in relation to consumers. Independent carbon crediting programmes are non-governmental initiatives that create and manage carbon credits and underpin voluntary carbon markets. They establish carbon standards for project design, validation, monitoring, and verification that are meant to safeguard the environmental integrity of the credits. A carbon standard is a set of rules, procedures, and methodologies or protocols that determine the generation and issuance of carbon credits. The standards ensure that project activities are measured, independently verified, and registered to issue unique carbon credits. Beyond managing these standards, carbon crediting programmes operate registries to track credit issuance, transfer, and retirement. This is meant to improve transparency and prevent double counting. Independent carbon crediting programmes with good governance maintain clear, transparent, effective and up-to-date rules and requirements, adequate mechanisms for stakeholder consultation and complaints, environmental and social safeguards, high-quality methodologies to establish the baselining and realised impact of a project, and clear requirements for independent third-party review of projects.

In addition to crediting programmes, international frameworks and integrity initiatives play a critical role in establishing best practices for both credit quality and their credible use. Complementing these, independent third-party rating agencies are expanding their influence by providing distinct assessments of credit quality. Lastly, a small but growing number of insurers offer products aimed at managing carbon-credit risks, particularly delivery risk for pre-issuance transactions and reversal risk for nature-based projects.

Mission Cities can tap into VCMs to compensate for residual emissions that are not regulated by compliance markets. They should be aware of several trends shaping the outlook of carbon markets leading up to 2030. First, compliance and voluntary markets are converging. As voluntary standards

are increasingly recognised within compliance mechanisms, competition between compliance and voluntary buyers for the same pool of eligible credits is intensifying. Second, overall demand is expected to grow significantly. This is driven by corporate buyers seeking to meet voluntary and net-zero commitments, domestic compliance markets, CORSIA requirements, and countries utilizing Article 6 of the Paris Agreement (World Bank, 2025). Third, there is a distinct "flight to quality". As market demand shifts from avoidance to removal credits, a shortage of high-quality removal credits is likely in the coming years, potentially driving up premiums for durable carbon removals.

**Box 11.** Potential and future opportunities for cities to purchase Article 6 removal credits

Article 6 of the Paris Agreement establishes a framework for countries to voluntarily cooperate to achieve their climate targets (NDCs), primarily through international carbon markets. While designed for nations, this framework also offers potential avenues for subnational governments and organisations to access high-integrity carbon credits to meet their own climate goals (South Pole, 2025a). Two key mechanisms underpin the Article 6 framework:

— Article 6.2 enables voluntary, bilateral cooperation between countries through the transfer of carbon credits (ITMOs - Internationally Transferred Mitigation Outcomes) to achieve targets in their NDCs. Countries can set their own rules while ensuring transparency and avoiding double counting through Corresponding Adjustments.

— Article 6.4 creates a UN-supervised carbon market mechanism (PACM - Paris Agreement Crediting Mechanism) that issues high-quality credits from emission reduction and removal projects. These credits can be used by countries to achieve NDC targets or by organizations to meet their carbon neutrality goals.

Potentially, cities can then procure Article 6 carbon credits to meet voluntary municipal climate goals and compensate for their residual emissions. In principle, three potential avenues could be explored:

— Authorised Credits under Article 6.2. A city can fund or procure carbon credits generated under Article 6.2 cooperative approaches that are explicitly authorised by the host country for "Other International Mitigation Purposes" (OIMPs). This specific authorisation triggers a Corresponding Adjustment (CA), whereby the host country agrees not to count the emission reduction towards its own target. This mechanism allows the city to access high-integrity credits for exclusive voluntary claims (such as climate neutrality), ensuring that the mitigation outcome is uniquely counted by the city and not "double claimed" by the host country.

— Centralised UN Mechanism (Article 6.4). A city could purchase Article 6.4 Emission Reductions (A6.4ERs) from the global market supervised by the PACM UN-supervised body. The city would need the authorisation from the host country as a voluntary buyer, and implementation of CAs shall be accounted for.

— Article 6-compliant VCM credits. Under this hybrid Voluntary Market Approach (Article 6.2), a city could purchase credits from established VCM standards that have received labels of Article 6 compliance, meaning that they will be correspondingly adjusted by host countries. To purchase credits from established VCM standards that have been approved for Article 6 use, the authorisation of the host country is needed.

It is important to note that Article 6 markets are still in their infancy; the pathways presented point to emerging possibilities based on the broad provisions under Article 6 rather than established transaction models. While the Article 6 rulebook has been finalised, its full implementation is still ongoing. In particular, the framework for using credits with CAs for voluntary purposes requires further consensus, as firm guidance has yet to emerge and accounting systems must still be fully developed and aligned with host countries. Nevertheless, looking ahead, cities should continue to monitor these developments to determine if the use of Article 6 credits can align with their residual emissions strategies. As implementation matures,

local governments might be well-placed to procure credits that come with high quality, integrity and credibility under UN oversight.

### 5.2.2 Credit quality, integrity and conditions within the Cities Mission

When approaching the purchase of carbon credits, the question surrounding their quality and integrity is vitally important. At the heart of this is whether the carbon credit accurately represents the climate impact and other socio-environmental benefits that are claimed. The quality of a carbon credit is directly related to the integrity of the activity that underlies the credit, also referred to as 'environmental integrity' (**Table 4**). Although often used interchangeably, quality and integrity represent distinct, albeit interconnected, aspects of a robust carbon credit. High quality refers to the scientific and technical credibility of the reduction or removal claim. A high-quality carbon credit is one whose underlying project activities are proven to be additional, measurable, verified, permanent, unique and create no harm. High integrity on the other hand builds upon the foundation of quality by encompassing the comprehensive integration of environmental and social aspects, alongside robust levels of transparency, good governance, and ethical practices.

**Table 4.** Environmental integrity attributes for carbon credits

| **Essential attributes** | |
|---|---|
| **Attribute** | Definition |
| **Real** | Carbon credit projects shall result in net carbon removals because of actual project activity and not as artefacts of inaccurate, incomplete accounting or double counting. |
| **Additional** | Carbon credit projects shall result in additional net removals, as compared to existing legal requirements, commitments, or regulation. In other words, the removals are beyond what would have happened in the absence of the incentive provided by the offset credit programme or project. This also means that the programme/project relies on the revenue from the sale of the carbon credit to be self-sustaining. |
| **Permanent** | Emission removals are irreversible or, if sourced from projects subject to potential reversal (e.g., due to wildfires, unintentional over-harvesting, droughts), have guarantees to ensure that any losses are compensated for. These may include replacement mechanisms such as i) legal guarantees, insurance, deed restrictions and conservation easements, which help to ensure that the geographic area in which the project takes place continues to be protected, and ii) buffer accounts or reserve pools, in which a percentage of carbon offset credits that a project produces is withheld and only used as compensation in the event that previously verified, or future expected, credits are eventually negated. Project owners are responsible for the permanence of credited carbon sequestration, through ongoing monitoring and periodic reporting and verification activities. On the other hand, contracts should clarify which party (i.e., the project developer or the credits buyer) is responsible to compensate for any/all losses of expected credits should the project fail to meet its permanence criteria. |
| **Sustainable** | Carbon credit projects shall address potential social and environmental impacts, ensuring they do not negatively affect ecosystems or local communities (Do No Significant Harm principle). The projects shall demonstrate safeguards against negative social and environmental impacts (e.g., protecting biodiversity, water resources, and community rights), ensuring that climate action does not come at the cost of other ecosystems. |

| | |
|---|---|
| **Measurable** | It shall be possible to quantify and verify carbon credit projects in a scientifically credible and accurate way. Quantification and monitoring shall be transparent, conservative, and follow established project accounting standards[6], ensuring reproducible results. |
| **Independently audited** | Carbon credit projects shall be verified by an independent, qualified, third-party verifier subject to a viable and trustworthy accreditation system (see page 24 and Annex B of (C40, 2019)). Where both validation (i.e., the process to determine the legitimacy of the baseline and methodologies used for a project) and verification (i.e., the process to determine that claimed offsets are real and additional when compared to the baseline scenario based on quantifiable evidence) are undertaken for a project, these two assessments shall be conducted by separate entities. Verification will be ex post, considering emissions removals that have already occurred. |
| **Transparent** | Carbon credit projects and their associated ID number shall be publicly and transparently registered. Credits should have unique serial numbers and the crediting process (e.g., issuance, retirement, project ownership) as well as the GHG emissions quantification methodology should be clearly documented. Information on the project validation (where applicable), verification, monitoring and enforcement arrangements (e.g., type of project, duration, location, validated project plan and verification reports for each vintage year, standards used, enforcement mechanism) shall also be made publicly available. |
| **Unambiguously owned** | Ownership of GHG reductions or removals is clear by contractual assignment and/or government recognition of ownership rights. Transfer of ownership of offset credits shall be unambiguous and documented. Once transferred (i.e., sold), all other parties (e.g., project developer, governmental authority/jurisdiction under which the project was developed, credit seller) cede all rights to claim future credit for the same offset in order to refrain from double counting. Ownership rights and transfer is clear by contractual assignment, being tracked and listed in a publicly available registry, with no more than one credit associated with a unit of GHG emission avoidance or sequestration. Interoperable public registries should ensure transparency and full traceability, so as to avoid the risks of fraud or double counting. |
| **No leakage (or reported and deducted)** | Leakage occurs if an increase in emissions from sources, sectors, or gases outside the project's emissions boundary occur as a result of the project's implementation. Leakages should be avoided over the life of a project. In the presence of avoidable or unavoidable increases in GHG emissions, these shall be reported and deducted from the abatement that would otherwise be counted towards the project's carbon credits. |
| **Desirable attributes** | |
| **Synchronous** | Credits can only be used to cancel out residual GHG emissions occurring during a distinct period of time that is reasonably close to the period of time during which the carbon sequestration will take place. This is particularly relevant to Mission Cities, in light of their 2030 deadline. |
| **Enforceable** | Carbon credit projects should be backed up by enforceable contracts incorporating the environmental integrity principles discussed in **Section 6.3** and in line with the other criteria or recommendations set out in this guidance document. |

*Source: JRC analysis (adapted from (C40, 2019; European Parliament and Council, 2024b; ICVCM, 2026; Levin et al., 2014)).*

The attributes detailed in **Table 4** are supported by the EU Carbon Removal and Carbon Farming Regulation (CRCF) (European Parliament and Council, 2024b) and aligned with the Integrity Council for the Voluntary Carbon Market (ICVCM) Core Carbon Principles (CCPs) as a global benchmark (ICVCM, 2026) (see also **Box 12**). They aim to guarantee accuracy and truthfulness in carbon credit claims, transparency and accountability in all aspects of the carbon-crediting programme, independent verification and validation along with robust tracking and monitoring of carbon credits, protection of environmental and social integrity, and alignment with net-zero emissions goals and sustainable development principles. Their application promotes carbon credits that have a real, unambiguously claimed and lasting impact on greenhouse gas emissions.

[6] E.g. World Resources Institute's Greenhouse Gas Protocol for Project Accounting; International Standards Organisation 14064-Part 2

The reality of implementing these principles in carbon projects is more complicated than the theory suggests. Carbon credits may be generated by projects in remote locations, involving complex climate and environmental processes, with impacts only realised over long periods of time and reliant on guarantees that come from third parties. In recent years, the VCM has come under criticism for not adequately ensuring the environmental integrity of the credits that are sold. Systemic quality issues have been identified in research showing that a significant number of issued credits did not correspond to actual emissions reduction, removal or avoidance (Probst et al., 2024). This has led to a range of revisions to existing carbon standards managed by the carbon crediting programmes and the launch of new overarching principles and initiatives to provide further safeguards (see **Box 12**). Ultimately, the quality of a carbon credit depends on the robustness of these standards and initiatives, how project developers apply them, and the rigour of third-party verification.

The definition of 'high-integrity' in the carbon market is constantly being shaped by a comprehensive landscape of initiatives and key players (South Pole, 2025b). Standard setters define rules and methodologies for climate projects. They accredit independent third-party auditors to verify project outcomes and are responsible for issuing carbon credits once verification is successful. Implementers, including project developers and other organisations on the ground, translate regulations and methodologies into tangible climate action, providing crucial real-world insights. Regulators, including government and regulatory bodies, establish and enforce laws, regulations and policies for carbon market activities. Rating agencies develop their own frameworks to assess carbon credits. This offers an additional, independent layer of scrutiny and transparency. Buyers and investors, typically companies and financial institutions, drive demand for high-integrity assets through their purchasing and investment decisions. The largest, most sophisticated buyers often publicly set their own proprietary quality frameworks.

Within the framework of the Cities Mission, any carbon credits used to compensate for residual emissions shall abide by the following conditions:

- They shall qualify as high-quality certified units as defined under the EU CRCF or be fully aligned with CRCF quality criteria (in the case of projects outside the EU). These criteria ensure the quantification of a net carbon removal or soil emission reduction benefit in a relevant, conservative, accurate, complete, consistent, transparent, and comparable manner. Activities shall comply with minimum sustainability requirements, be additional, and ensure storage, with monitoring rules and liability mechanisms to address reversal risks. The European Commission recognises certification schemes that operate on reliable, transparent rules to ensure activities and their resulting certified units meet the Regulation's criteria. This is explained in **Section 9**.
- They shall not originate from activities the city has excluded from the target boundary. This condition shall be respected to avoid the paradox where cities propose exclusions from the target and then claim carbon credits from activities on those exclusions (see **Box 2**). Cities that buy credits from third parties within their boundary can do so to e.g., contribute to financing a given removal activity. However, any share of credits sold outside the boundary cannot be claimed. This is typically the case of large carbon removal projects that require multiple streams of investment.
- They result from verified carbon credit projects, not local carbon contributions or carbon offsetting programmes or funds, which are instruments designed for local stakeholders to make up for their emissions by investing in in-boundary climate mitigation projects (see **Box 13**) and serve as instruments to incentivise emissions reductions.

**Box 12.** Integrity initiatives for carbon markets and corporate climate action

Over the years, a number of governance initiatives and overarching quality standards have been launched to strengthen the integrity of the VCMs in the absence of regulatory oversight, the carbon crediting programmes, their carbon standards and the carbon credits issued. For some VCMs, the introduction of these initiatives has created renewed trust in the power of carbon markets. For others, they have added to the confusion. In practice, carbon crediting programmes seek to become compliant with such 'meta standards', while ensuring that their credits can be said to align with the highest quality criteria. Leading initiatives in the VCM include:

- The **Integrity Council for the Voluntary Carbon Market (ICVCM)**. It is a non-profit, independent governance body established with the aim to develop and safeguard the highest standards of ethics, sustainability, and transparency for the VCM (ICVCM, n.d.). By setting and enforcing a global benchmark for high-quality carbon credits in the form of its Core Carbon Principles (CCPs), ICVCM offers a global benchmark for high-integrity carbon credits. The ICVCM evaluates carbon crediting programmes and carbon credit methodologies against its CCPs under an Assessment Framework. Programmes become CCP-eligible and methodologies CCP-approved when they meet the ICVCM's requirements. The ICVCM's remit includes assessing programmes that issue carbon removal credits, as well as the carbon removal methodologies themselves.
- The **International Carbon Reduction and Offset Alliance (ICROA)** is an industry trade group for providers of carbon credits (ICROA, n.d.). ICROA's independent assessment of carbon crediting programmes is based on review criteria that apply primarily at the organisational level, rather than individual standards or protocols. When reviewing programmes, ICROA assesses their independence, governance, registry, validation/verification, carbon crediting principles, environmental and social impacts, stakeholder considerations, and scale. A carbon crediting programme can become ICROA endorsed if it is successfully assessed against ICROA's Endorsement Criteria. ICROA covers programmes that issue carbon removal credits. As of December 2025, ICROA has announced that it will wind down operations by late 2026, stating that the ICVCM and VCMI initiatives are well placed to continue the work that ICROA began.
- The **Carbon Credit Quality Initiative (CCQI)** was created by a consortium of NGOs, including the Environmental Defense Fund, World Wildlife Fund and the Oeko-Institut (CCQI, n.d.). It provides transparent information on the quality of carbon credits, helping users identify the types of carbon credits that are more likely to deliver emissions compensation and social and environmental benefits. CCQI offers a free, user-friendly tool to score different types of carbon credits against seven quality objectives. As for carbon removal credits, it currently only looks at afforestation projects, though other carbon removal project types may be included at a later stage.
- The **Voluntary Carbon Markets Integrity Initiative (VCMI)** is a global non-profit governance body giving guidance on the use of carbon credits by companies and other non-state actors such as cities (VCMI, n.d.). The VCMI Claims Code of Practice sets a standard for how to use credits as part of credible, science-aligned, net-zero decarbonisation pathways. It builds trust and confidence in how companies engage with VCMs, assisting them in making credible climate claims. The VCMI also maintains an Access Strategies Program to guide countries on how to engage in high-integrity VCMs.
- The **Science Based Targets Initiative (SBTi)** is a non-profit, UN-backed corporate climate action coalition of the WRI, WWF, CDP and the UN Global Compact (SBTi, n.d.). It was created to help companies establish climate targets in line with science. It developed the first net-zero standard, including guidance and tools for addressing scope 1, 2 and 3 emissions. It validates corporate decarbonisation targets against this standard. SBTi has also developed rules for the use of carbon credits as part of a company's climate action effort, including carbon removal credits. SBTi allows cities to submit an SBT but does not validate them as of yet.

**Box 13.** Is an "offset" always a residual emissions compensation mechanism?

"Local carbon offset funds", "local climate finance facilities" (or similar) are pools of money that cities or organisations can establish to invest in any climate change mitigation project like reforestation, renewable energy, or energy efficiency initiatives. They are means to monetise any shortfall with respect to specific climate mitigation objectives. Let's take the example of GHG emissions reduction objectives for private buildings. If the energy retrofits and upgrades are insufficient to reach the target, owners may have the option to temporarily buy "offsets" by paying into a citywide carbon fund. The fund would be used to finance or subsidise building energy efficiency upgrades that would take longer if only driven by market factors (C40, 2019). This and other similar mechanisms, while sharing the underlying principles of carbon offsetting contribute to local GHG emissions reduction or removal, but do not represent nor require carbon crediting.

This note is of particular relevance in the context of the Cities Mission, as the analysis of the Expressions of Interest revealed that a number of eligible cities, in discussing a possible residual emissions strategy, claimed emissions offsetting via investments in local projects through the activity of local carbon cooperatives, local compensation platforms, voluntary local carbon offset funds, or climate accounts. These mechanisms may not respect the conditions on carbon credits outlined in this Section.

### 5.2.3 City decision-making around carbon credits

Building a carbon credit strategy and portfolio to support net-zero goals requires cities to navigate multiple questions and choices, ranging from strategic preferences to risk considerations, from purchasing arrangements to claims and communication. A step-by-step approach can be followed to effectively deal with these questions, make purchase decisions, and to set up a strategic, long-term approach for mitigating risks, ensuring compliance, and aligning the portfolio with net-zero goals (South Pole, 2026).

When dealing with carbon credits and their lifetime (**Box 9**), cities are called upon making multiple decisions:

— **Use credits or not?** As mentioned, cities can use verified removal carbon credits to compensate for residual emissions. Beyond this, credits can serve complementary purposes. For instance, they may be leveraged by cities to stimulate the involvement of the private sector in climate action or to foster climate solidarity within the EU (when credit-generating projects are implemented in other Member States, especially in lagging regions). However, there is a risk of shifting efforts away from local carbon removal. The consequence is that the benefits of the emissions removal associated with the credit may not be enjoyed by local communities. This is particularly relevant in the case of environmental ecosystem services such as improvements in air, water and land quality, food security, local biodiversity, and disaster risk reduction. A form of "peer solidarity" could also be established with neighbouring or affiliated municipalities, to intensify local co-benefits, territorial cohesion, and inter-city cooperation. This would create opportunities for flexible collaboration, enhanced technology transfer, and capacity building. As carbon removals - notably those associated with natural carbon sinks - have a role to play also in building up the city resilience against the impacts of climate change (i.e., climate adaptation, see also **Box 22**), cities may consider saturating their natural sink capacity before opting for carbon credits generated through out-of-boundary projects. Furthermore, it may be more cost-effective to take early domestic action rather than rely on purchased units later in time, as price volatility may result in overall higher costs (see **Section 6.6**). Ultimately, the decision of a city on the extent to which it will leverage carbon credits vis-à-vis in-boundary carbon sinks to balance its residual emissions should be rooted in local considerations.

— **What project type?** The question of the type of carbon credit is directly related to the underlying project, including the carbon removal method and the durability of the storage. The EU CRCF lays out a choice among three removal categories: permanent carbon storage (e.g. geological), carbon farming (e.g. soil, agroforestry, peatland) or carbon storage in long-lived products (e.g. bio-based construction materials). The decision-making process across different carbon credit options should follow quality principles, as addressed in **Section 6**. While all mentioned principles are aimed at genuine and effective climate action, "transparency" and "environmental integrity" constitute mandatory principles in the framework of the Cities Mission, for both carbon removals and carbon credits.

— **Where?** The question relates to where carbon removal projects shall be located, and if there are any regions or countries cities wish to prioritise or exclude. While carbon has a global impact regardless of where it is removed, choosing locations where cities have strategic connections (e.g., significant supplier base) allows them to create a positive impact where they operate and have a more authentic and tangible climate contribution and narrative. It could also demonstrate a direct commitment to specific technologies, surrounding communities, and co-benefits.

— **What standards and additional checks?** Carbon removal credits that are CRCF-certified are generated from projects using methodologies that are verified according to CRCF criteria and hold this label. Depending on their preferences, cities can still favour certain standards or registries, as well as use third-party ratings, provided they are fully aligned with CRCF quality criteria.

— **What co-benefits?** This question relates to the opportunity for cities to deliver co-benefits (e.g., social and community, environmental and biodiversity, economic and infrastructure) when purchasing removal credits (see also **Section 6.4**). By assessing if and which co-benefits a project develops, cities can further align with their (local, national and international) strategies and further deliver impact.

— **What vintage?** The vintage is the year in which the emissions removal associated with the credit occurred or is expected to occur. Cities can collect vintages of offset credits from multiple years as from an accounting perspective this is not problematic. However, on the premise that the magnitude of residual emissions may vary over time due to contextual changes, methodological upgrades, technological advancements, funding schemes or financing mechanisms (that may open up the opportunity for further emissions reduction at source), Mission Cities are encouraged to privilege vintages closer to the target year and avoid accumulating an excessive surplus of credits across vintages.

— **What city role?** This question directly relates to the way cities want to structure the volume and timing of their purchase. Cities can approach carbon credits taking a number of roles: i) carbon credit projects **developers**, by taking responsibility for managing the project over its lifetime (including on the ground activities and possibly the certification process); ii) carbon credit projects **investors** by funding the project, committing to purchasing a set quantity of future vintages, or providing upfront funding for credit registration costs; or iii) carbon credits **buyers** from a registered/credible/established carbon credit registry (e.g., Puro.Earth, Gold

Standard, Verra)[7]. Cities therefore have the option to invest in project development, structure multi-year forward offtakes, or engage in spot purchasing (see **Section 6.6**). The choice is very much city-specific and highly depends on the city capacity to technically and/or economically support carbon credits. Furthermore, cities could individually or collectively enter into long-term offset purchase agreements, similar to power purchase agreements. Such agreements (designed as e.g., Contracts-for-Difference) would provide long-term guaranteed revenue streams, allow developers to finance carbon projects upfront, and provide price certainty for credit users (M. Allen et al., 2020). Similarly, cities could form or encourage sector-specific alliances to leverage shared opportunities and involve the private sector in clearer and stronger stances in climate action. Public procurement could be a means of unlocking cost savings by aggregating purchasing volume (see **Box 14**). The decision on the city role around carbon credits is connected to the extent and modality through which revenues are meant to be invested (see **Box 15**) and forms part of a broader decision-making process in the context of residual emissions strategies (see **Box 7**).

— **What claims and communication?** Cities will have to make important decisions on how to communicate about their investments in carbon removal credits. Net-zero claims should be accompanied by a city-wide climate narrative, transparently showing why the city supports specific carbon projects and the global impact they create (see also **Box 18**).

**Box 14.** Collective public procurement programmes

This box outlines various best practices and describes the merits of shared public procurement of carbon removal credits to balance out residual emissions.

Public procurement in the carbon removal space was pioneered by the US Federal Government as a means of 'pulling' market demand for carbon removal. In September 2023, the US Department of Energy launched the CDR Purchase Pilot Prize. The $35 million was intended to directly purchase permanent CDR from domestic suppliers across a number of CDR methods. The initiative was flanked by a Voluntary $CO_2$ Removal Purchasing ($CO_2$ RP) Challenge that called on other organisations to purchase small and growing quantities of high-quality, permanent CDR credits from the same list of suppliers (U.S. DOE, 2024).

While the CDR Purchase Pilot Prize has been put on hold, the European Commission is now taking decisive steps towards the creation of an EU purchasing programme for permanent CDR involving tech development support, market development, high-quality procurement, and effective governance. The proposal for the short term (2025-2030) includes an EU Removals Fund, combined with the EU Coordinated Buyers Club and Centralised Procurement Agency for EU Member States. On 21 May 2025, DG CLIMA organised a workshop that was facilitated by the Ecologic Institute to inform the study on the design and near-term implementation of such a potential purchasing programme for CRCF permanent carbon removal credits (Ecologic Institute, 2025). As a follow-up, DG CLIMA published a report "An EU Purchasing Programme for Permanent Carbon Removals: Assessment of Policy Options and Recommendations for Short-term Policy Design" that looks at different options for purchasing CDR at EU level (European Commission & Ecologic Institute, 2025). It explores the potential role of the proposed EU-wide purchasing programme and how it could create demand for permanent CDR in the short-term (2025-2030), a timeline that is very relevant to Mission Cities. To help grow the market, it recommends strategically purchasing various types of removal credits and using a mix of funding sources, including the EU budget, contributions from Member States, and

[7] Not all credits from trusted registries are high-integrity. Therefore, it is important to look for additionality and permanence. With the EU CRCF emerging as a certification framework for Member States and cities, it is advisable to future-proof the city strategy already today by choosing providers ready to align with CRCF.

private funding (see also "Diversification Principle" **Section 6.5**). A complementary report by DG CLIMA and Ramboll Management Consulting maps and assesses in more detail existing EU funding programmes such as Innovation Fund or Horizon Europe that support CDR and explores innovative funding models to strengthen early-stage CDR projects (European Commission & Ramboll Management Consulting, 2025b).

Centralising pooled funding from Member State contributions along the lines of an 'auction-as-a-service' model holds significant promise at the level of cities. CDR projects make bids to offer carbon removal at the lowest price point, with the city government selecting the most cost-effective bids, promoting competition and efficiency both within and between different CDR pathways. This mechanism allows governments to shape the volume, price and quality of carbon removal over time, building trust that incentivises private sector buyers to buy high quality carbon removal credits.

When public procurement is shared, this is also known as cooperative purchasing or joint procurement. Mission Cities can coordinate efforts by creating a shared public procurement mechanism or platform. Through cooperative purchasing, multiple cities join to leverage their collective buying power, unlocking cost savings by aggregating purchasing volume and enabling cities to negotiate better terms and conditions, reducing risks by giving access to a wider network of suppliers, and creating time efficiency by streamlining procurement processes and reducing administrative burden. Finally, cooperative purchasing can create the critical mass of demand needed for private investment to step in (C40, 2024).

There are examples of shared procurement in Europe that can be built on for the purpose of carbon removal credit procurement by cities. The Big Buyers Working Together (BBWT) project, managed by EuroCities, ICLEI and BMW under the supervision of the European Commission, facilitates joint procurement activities through so-called Communities of Practice (CoPs). The CoPs focus on specific products, work or service areas where there are clear benefits in collaborating at the European level. These CoPs offer a platform for public buyers to share knowledge and best practices and launch cooperative procurement projects. Mission Cities may be inspired by a similar model.

The private sector also offers valuable examples and inspiration, building on the experience of corporate buyers' alliances such as TechGen and the NextGen CDR Facility. These initiatives are designed to de-risk CDR investments by aggregating demand from leading multinational buyers, thereby sending a strong market signal to developers. By pooling purchasing power, these clubs grant members reliable access to high-quality removals at more accessible prices while collectively supporting the scaling of new technologies.

Even though cooperative public procurement of CDR credits by cities has not yet been implemented, there are pioneering efforts that pool funding from multiple cities to generate grants into CDR project development. The 4 Corners Carbon Removal Coalition in the United States is a collective of six cities that have formed a partnership to provide joint catalytic funding into projects in one of their locations. They issue open calls on a shared platform where CDR contractors can make a bid to be awarded the funding. Once a contract has been awarded, the cities jointly seek out additional sources of funding in collaboration with the contractor to realise the project.

**Box 15**. Credit revenues can and should be used strategically to unlock higher ambition in climate action

Cities can unlock higher ambition in climate action through the strategic use of carbon credit revenues. The sale of carbon credits on the VCM by municipalities is potentially an opportunity for cities dealing with steep greenhouse gas reduction targets and few revenue generation opportunities to make the necessary investments. Engaging in VCM offers local municipal revenue opportunities for cities to raise capital that can be channelled into climate projects within their boundaries (Clean Air Partnership, 2025).

However, a primary challenge is demonstrating additionality, i.e., proving the project requires carbon finance, which becomes increasingly difficult amidst expanding regulations and existing city commitments. Furthermore, in Europe, the business case is often strained by high implementation costs, resulting in credit prices that may be unattractive on the global market. These economic barriers are compounded by the

delayed nature of carbon revenues, which typically materialise years after project inception, and the substantial administrative burden of third-party certification. Finally, acting as a seller requires cities to navigate complex accounting rules to prevent double counting and ensure the highest integrity in their revenue and climate claims.

When it comes to cost-benefit analyses, municipalities are advised to take into account the transaction costs related to the sale of their carbon offset credits and the risks with developing carbon projects. Third-party costs are associated with registry fees, verification fees, transaction fees, and potentially carbon accounting methodology development fees. Such costs depend on the registry that is used, complexity of the verification process, and the novelty of the carbon removal solution. Costs may also increase as a result of invalidation and reversal risks, when more credits are sold than the carbon sequestered or when sequestered carbon is released due to unforeseen natural developments. Meanwhile, revenues may end up lower than expected due to market fluctuations causing drops in the price of carbon (Freedberg & Smith, 2021). Cities are advised to map such risks in advance to ensure the long-term success of any municipal carbon programme.

Cities shall also take into account the effect of carbon credit selling on the ability to count the carbon removal in their GHG inventory and claim the climate impact. If a municipality sells carbon removal credits that it has generated under a public carbon programme to an entity outside its boundary it can no longer count it as part of its inventory. Creating a satisfactory balance of costs and benefits may be different when considering carbon removal projects. This relates to the nascency of many of the solutions, a city's possible preference to leverage the programme to secure the co-benefits or improved ecosystem services that come with more resilient ecosystems, raise the capital needed to invest in protecting such local ecosystems, or catalyse the local climate action innovation landscape.

Another critical decision for cities is how to direct carbon credit revenues, applicable to both credits generated within and outside their target boundaries. The Cities Mission emphasises the importance of utilising these revenues to enhance effective climate action and potentially increase a city's net-zero ambition. An illustrative example is provided by the hypothetical city of Europia. Europia encounters significant financial constraints in developing the necessary infrastructure to reduce its transport emissions. Building the needed infrastructure could reduce emissions by X%. To address this challenge, Europia implements an in-boundary credit-generating project, achieving Y% emissions removal. The resulting carbon credits are sold, generating Z € in revenue. Although the associated emissions removal can no longer be claimed by the city in its emissions inventory, the revenue is reinvested in building the required transport infrastructure, unlocking the associated X% reduction in emissions.

This strategic use of carbon credit revenues can yield positive impacts in two primary ways:

— **Local benefits:** the city continues to benefit from the emissions removal activity, including associated co-benefits.

— **Emissions reduction:** the city achieves X% reduction in emissions.

When X% exceeds Y%, the net result on the emissions balance leads closer to net-zero compared to the case where the removal is not credited and sold. Moreover, if the investment in transport infrastructure generates its own revenue streams (e.g., metro ticketing, with utilities partially or fully owned by the city), this could provide an additional funding source. This could be utilised to further reduce emissions (as a priority option) or purchase credits, making up for those previously sold.

The key takeaway is that the establishment of a municipal carbon programme offers significant opportunities for cities to realise climate impact, but requires extensive due diligence, involves complex risk management, and long-term resource commitments. Cities should consistently allocate carbon credit revenues towards climate action initiatives, fostering self-sustained mechanisms that drive increased ambition and progress toward a net-zero future.

**Cities in the spotlight: Łódź (Poland) and Tampere (Finland)**

In the first iteration of its CCC, the City of Łódź proposes a clear plan for carbon credits, which specifies the types of projects, their origin, and crediting frameworks along with an estimation of the share of residual emissions covered (93%) and of the costs involved (EUR 7-14 million) (Łódź, 2025). Projects include carbon forests, sustainable farming practices, peatland habitat restoration with a focus on projects in Poland and other EU countries or EU neighbouring states. The attention to credits does not entail disregard of other emissions compensation options, but a critical analysis of their (limited) potential. Delivering on a multipurpose agenda, the city is targeting: revitalisation of parks and green areas, creation of new urban forests and parks, creation of pocket parks near residential buildings, greenery along the city's public transport communication system, restoration and revitalisation of river valley areas, and other urban greening activities. The city is also exploring the use of BioCCS, in consultation with industry.

As part of its Climate Neutral Tampere 2030 Roadmap, Tampere is developing a comprehensive strategy to compensate for its residual emissions. This involves balancing the use of local carbon sinks with an evaluation of the options for the strategic procurement of carbon credits. With support from NetZeroCities and consortium partner South Pole, the city assessed its options for building a long-term carbon credit strategy to meet its 2030 net-zero target. The analysis focused on developing forward-looking portfolio scenarios based on the city's specific preferences, sourcing needs, and strategic priorities. The selection of carbon projects was guided by key criteria, including alignment with the city's preferences (on technology, co-benefits, geographies), national and EU guidelines, cost-effectiveness, and risk management. Using real carbon projects and price forecasting, four distinct portfolio scenarios were modelled to assess the feasibility and cost implications: i) a globally-sourced portfolio, transitioning from high-quality nature-based avoidance projects to 100% carbon removals; ii) a portfolio focusing exclusively on high-permanence removals sourced within the EU; iii) a strategy with a heavy reliance on high-permanence, engineered removal projects; and iv) a portfolio prioritising nature-based removals to maximise co-benefits such as biodiversity and social impact. The scenario analysis provided critical insights for Tampere's planning process, highlighting:

— The potential budget and investment required to meet the 2030 net-zero commitment.
— The strategic value of a diversified portfolio for managing price, delivery, and reputational risks (see also **Section 6.5**)
— The opportunity to prioritise projects with high co-benefits to maximise social and environmental value (see also **Section 6.4**).
— The importance of acting early to secure the availability of high-quality, high-integrity credits in a competitive future market (see also **Section 6.6**).

# 6 Guiding principles

To ensure that removal efforts are effective, sustainable, and equitable, cities should adhere to a set of guiding principles that should be considered holistically to avoid unintended consequences and maximise the impact of residual emissions strategies. At the heart of these principles is the recognition that:

- Emissions compensation is never a substitute for feasible emissions reductions, which always remain the priority.
- Transparency is essential, with cities expected to reliably measure and document their emissions and removals.
- Environmental and ethical integrity is key to avoid harm to the environment, human health and social systems.
- Co-benefits and diversification are levers to maximise the positive impacts of compensation strategies and minimise risks and uncertainties, while cost and time effectiveness ensure affordability and timeliness.

In the following each principle is presented and discussed individually.

## 6.1 Emissions reduction first

Carbon removal cannot replace emissions reduction and over-reliance on it risks deterring reduction efforts and delaying the fossil fuel phase-out (Peters, 2016).

To ensure the application of the Emissions Reduction First Principle, cities on a climate-neutral pathway within the Cities Mission's framework are encouraged to make continued efforts to update emissions reduction trajectories, maintain an updated estimate of residual emissions based on planned and implemented action, and catalyse additional climate action to maximise the effective emissions reduction potential, as new mechanisms, technologies, and opportunities become available. Every year of delaying rapid and sustained emission reductions increases the requirements for CDR deployment in the long term (S. M. Smith et al., 2023), ultimately increasing system-wide spending (Shindell & Rogelj, 2025).

In the pursuit of net-zero emissions within the Cities Mission's framework, emissions reductions should be prioritised over compensation at any step of the city pathway to climate neutrality, with the Climate City Contract offering the flexibility to adjust the action planning as the context evolves. This is crucial as research and innovation move fast in delivering new means of reducing emissions and more opportunities arise as local governments implement demand-side measures and stimulate behavioural change. Unless the decision to pursue CDR responds to other reasons and goals than to compensate residual emissions, Mission Cities are required to resort to compensation mechanisms only where current and next-future options to reduce emissions have been exhausted (i.e., anticipation of new solutions would be instrumental) or where social, technical, or financial obstacles are insurmountable (see also **Section 4**). This calls for an approach that ensures an ongoing and dynamic balancing of reduction and removal efforts in the planning and implementation of interventions to achieve climate neutrality.

While this is the core of the Emissions Reduction First Principle, it also translates into guarantees that where residual emissions exist, compensation mechanisms do not trigger side effects that would offset the net positive impact on emissions. While there are co-benefits that may be realised,

(unintended) adverse effects of carbon removal can equally be triggered, including a net increase in emissions (see **Sections 6.3 and 6.4**). Maintaining a detailed overview of potential co-benefits, adverse effects, and trade-offs is vitally important for a high-integrity residual emissions strategy. This allows for informed decision-making, risk mitigation, and maximisation of positive impacts (Förster et al., 2022).

The Emissions Reduction First Principle has also a very practical vein. Deploying large-scale carbon dioxide removal is often heavily constrained by investment costs, geopolitical factors, biological, geological, technological, and institutional limitations. For instance, in the use of natural sinks, concerns arise on biodiversity and native species preservation, carbon sequestration reversal, as well as on the fact that climate change itself is destabilising some terrestrial carbon reservoirs (Hubau et al., 2020; Korosuo et al., 2023). While this arguably strengthens the case for nature-based solutions to mitigate climate risks, it also raises questions about relying on them too heavily for net-zero claims (Fankhauser et al., 2022). In the case of geological storage, the low risk of physical reversal is contrasted by a large uncertainty about the appropriate rate of injection and the geo-mechanical response of the reservoir (Pianta et al., 2021). The public understanding and acceptability of subsurface geological storage is also still evolving (Fankhauser et al., 2022). Emerging options, such as soil carbon sequestration, ocean alkalinisation and mineralisation need further development to ascertain their safety and effectiveness at scale and in specific contexts (Fuss et al., 2018). This framework of uncertainty that currently characterises compensation strategies, endorses and corroborates the need to prioritise emissions reduction at source, while taking a measured approach to the use of carbon removal to balance residual emissions. Pilot and demonstration projects are vital for ensuring the local suitability of any CDR pathways considered for deployment at scale.

Emissions reduction and compensation should be seen as complementary approaches where reduction comes first whenever possible. As discussed in **Section 5**, the IPCC calls for removals to complement reductions by accelerating climate change mitigation today, balancing residual emissions by net-zero, and addressing legacy emissions to go net-negative emissions. Removal methods can deal with sources of anthropogenic emissions as well as legacy emissions already accumulated in the atmosphere and troposphere, against which emissions reduction today has no effect. Separate targets (see **Box 16**), adequate regulation of the use cases of CDR, along with oversight transparency and quality assurance, can neutralise the moral hazard of carbon removal delaying emissions reductions.

**Box 16.** Three may be better than one: the latest recommendations on target setting

The European Scientific Advisory Board on Climate Change, in its report 'Scaling up carbon dioxide removals – Recommendations for navigating opportunities and risks in the EU' (European Scientific Advisory Board on Climate Change, 2025), recommends setting separate legal targets for 1) emissions, 2) temporary removals from land, and 3) permanent removals from novel CDR methods. The ultimate goal is to enhance the transparency and environmental integrity of the overall strategy (see also **Sections 6.2 and 6.3**), provide clear investment signals, promote technological progress, and decouple compensation from emissions reduction targets, thus encouraging social acceptance of removals and possibly dispelling accusations of mitigation deterrence.

Within the Cities Mission's framework, cities are not required to set three separate targets. However, they are encouraged to investigate the potential benefits of this approach, especially if it can help them achieve their objectives more effectively.

## 6.2 Transparency

Residual emissions and the associated compensation strategy should be dealt with in a way that is transparent to the general public. The Transparency Principle emphasises the importance of reliably measuring and documenting all emitting activities and relevant emissions - both positive and negative - by sector, alongside the management of sold and retired credits, in a manner that prevents any possibility of double counting. Rigorous application of this principle is crucial to verify that net emissions amount to zero at the closure of the target year (2030 for Mission Cities).

Net emissions take into account both GHG emissions/removals (associated with the scopes, sectors, sources, and gases included in the climate neutrality target) and carbon credits. They represent the difference between a positive term made up of GHG emissions ($GHG^{+}$) and sold credits ($CC_{sold}$) and a negative term that includes GHG removals ($GHG^{-}$) and retired credits $CC_{retired}$, as follows:

$$GHG_{net} = \sum_{i,j,k} GHG^{+} + CC_{sold} - \left| \sum_{i,j,k} GHG^{-} \right| - CC_{retired} \quad (1)$$

where i indicates the scopes, j the sectors/sources, and k the gases included in the climate neutrality target. GHG removals from carbon credits retired (bought) count as negative emissions, while GHG emissions from carbon credits sold count as positive emissions and would add to the total GHG emissions to be mitigated. However, it is noted that only if $GHG^{-}$ takes into account the emissions removal associated with the carbon credits sold, then the relevant $CC_{sold}$ needs to be added (otherwise those removals would appear as positive emissions).

The Transparency Principle translates into three key rules:

— The **individual terms** in **Equation (1)** should be **reported separately**. For $GHG^{+}$ and $GHG^{-}$ a sectoral breakdown would be required to better appreciate the origin and contribution of emissions and carbon removals. A further breakdown into different sources – such as land uses or activities – and gases would be appreciated but does not constitute a mandatory requirement.

— Carbon credits shall always be issued in a publicly available registry to ensure **transparency and traceability**. In Europe, the CRCF Regulation mandates the establishment of a Union registry by December 2028, which the Commission will maintain. Until then (and outside the Union), recognised certification schemes should maintain interoperable certification registries that make information publicly accessible in a secure way, using automated systems and electronic templates. The Commission will adopt implementing acts setting out the structure, format, technical details, and rules for recording, holding, or use of certified units for these registries. The information that is required to be published under the CRCF is: the name and type of activity, operator details, geographically explicit location of the activity boundaries, duration of the activity period, name of the certification scheme/body, a unique certificate number or code, a reference to the applicable methodology, the quantified net benefit and its components, sustainability co-benefits, the monitoring period, details on liability mechanisms, certification status, and the quantity and validity of certified units. A clear accounting system should be in place for all offsetting activities happening within the city that produce credits (including by private companies or individuals). The way they are factored in the emissions inventory should be documented, including a commentary on how fraud and double counting risks have been averted or minimised (see also **Box 19**). The CRCF framework itself includes measures aimed at averting or minimising fraud and double counting risks through requirements for independent third-party auditing by accredited bodies, the use of certification schemes recognised by the Commission, and the establishment of verifiable registries. While the specific requirements of the CRCF Regulation apply to removal projects in Europe, the same principles of transparency, traceability, and accountability should be applied to projects outside Europe, ensuring that similar measures are taken to prevent fraud and double counting.

— For a correct estimation of $GHG_{net}$ there needs to be **absolute clarity regarding what is included and excluded in the calculation, as well as consistency between the target and the residual emissions strategy** (see also **Box 2**). If a sector or source of emissions is included in the residual emissions strategy (e.g., as a sink and hence as part of $GHG^{-}$), any positive emissions released from the same sector or source need to be accounted for in the calculation of $GHG^{+}$. A frequent misconception that would raise a red flag in the context of the Cities Mission, is to include “forestry” or “other land use” as part of the compensation strategy (and thus account for the negative emissions that would be generated) even when the AFOLU sector is explicitly excluded from the climate neutrality target (and thus from the baseline emissions inventory). This “selective” approach to emissions accounting undermines the legitimacy of the city’s net-zero pledge. To avoid this, the city is required to transparently account for both positive (e.g., trees maintenance emissions) and negative emissions (e.g., carbon removals by trees) associated with the same source and report each contribution clearly in its CNAP. In the example, as the “agriculture” or “fisheries” components of AFOLU do not feature in either the target or the residual emissions strategy, they may be consistently omitted. To ensure clarity, we will refer to the "**corrected target boundary**" throughout this document. This means the target boundary set by the city, adjusted to include any sectors that are part of the residual emission strategy. For instance, if a city's target boundary initially excludes "forestry" or "other land use", but includes them in the compensation strategy, the corrected target boundary would be the original target boundary with "forestry" or "other land use" added to it.

**Box 17.** Transparency in the land sector

Beyond accounting complexity (see **Section 7.1**), the land sector poses some challenges even in target setting and in the transparent reporting of potential exclusions. Cities are invited to specify if any of the following land units are included (or excluded) from the target boundary: land units subject to protection, to restoration, or to high climate risk. Concerned categories are listed in Annex V Part 3 of the amended Land Use, Land-Use Change and Forestry (LULUCF) Regulation – see **Section 9**.

Overall, full disclosure should be ensured on the activities behind positive and negative emissions as well as carbon removals and credits, to demonstrate the anthropogenic nature of negative emissions (see **Box 3**), rule out double counting, promote co-benefits, and guarantee that credits meet key criteria (e.g., permanent sequestration – see **Table 4**).

It is noted that this level of transparency is instrumental to build enough evidence and experience to lower the risk profile of compensation mechanisms (in particular large-scale implementation), guarantee robust and harmonised certification processes, highlight best practices, and promote the market for emissions compensation, while minimising the administrative costs for public authorities. For instance, evidence suggests that many stakeholders do not trust carbon removal certificates because certificates may be generated through non-transparent and unreliable certification processes which certify activities that are not delivering true climate and sustainability benefits (European Commission, 2024). The Transparency Principle aims at lifting these barriers.

The Transparency Principle also translates in providing full access to sufficient information to rebuild the methodological steps used for accounting, monitoring, reporting, and verification. This includes anything from the selection of emission factors to the treatment of natural disturbances (see **Box 25**).

Furthermore, to increase transparency and clear communication, cities should disclose publicly their strategy to reach climate neutrality and the priorities, principles, and expected outcomes that have guided the process. Notably, the rationale for the use of in-boundary carbon removals or out-of-boundary credits should be communicated clearly and the benefits should be explained thoroughly with due attention to environmental, economic, ethical, and societal considerations. Different communities and groups should be reached, with the intention to symmetrically raise awareness on the potential opportunities and challenges from the use of compensation measures, in particular in-boundary carbon removals (see **Box 18**).

**Box 18.** The importance of transparent public engagement

The Transparency Principle also concerns the decision-making process. The responsible scale-up of carbon removal involves complex social and ethical questions and includes both policy-level public engagement and project-specific community engagement (Lin, 2025) (see also **Section 6.3**). As a corollary of transparent policymaking, general and targeted public engagement is critical for ensuring the social legitimacy of carbon removal policies and support from affected communities. Providing clear and accessible information about project details and potential impacts, helps build the necessary trust and fosters buy-in from such communities. This requires inclusive communication and public participation in decision-making processes (European Scientific Advisory Board on Climate Change, 2025).

In addition to engaging the general public, transparency also implies the need for adequate engagement that gives a voice to local communities where projects are deployed, making it possible to adapt project plans, address specific concerns and needs, and ensure that CDR policies do not reinforce existing or

historical injustices. Incorporating equity and environmental justice principles can maximise benefits, minimise risks, and ensure a fair distribution of both. The practice of requiring project developers to adopt 'community benefit plans', in close consultation with affected communities, can give a practical framework for structurally integrating communities in the development and deployment of projects (WRI, 2025).

## 6.3 Environmental and ethical integrity

Both in-boundary carbon removals and out-of-boundary carbon credits should be leveraged to deliver net-zero targets with careful consideration of potential unintended negative impacts. The Environmental and Ethical Integrity Principle is a requirement to be met for any compensation strategy to genuinely contribute to a city's climate neutrality goal.

When scrutinising CDR options, permanence is a highly desired characteristic. However, as discussed in **Section 5**, temporary removals can (and in some instances should) be still prioritised, notably when they better respond to the Co-benefits Principle (see **Section 6.4**). Potential reversals need to be monitored, reflected in the emissions inventories, and dealt with through buffers while promoting continuity in action and remedial interventions - e.g., continued ocean fertilisation, diversified forestation in terms of tree species and age.

**City in the spotlight: Greater Dunkirk (France)**

The CNAP by Greater Dunkirk stands out for its strategy against potential reversals (Dunkirk, 2025). To minimise the risks associated with non-durable emissions sequestration, Greater Dunkirk has developed a comprehensive approach that combines:

- **Monitoring and early detection**: establishing long-term monitoring systems to regularly assess the stability and effectiveness of natural carbon sinks, enabling early detection of potential reversals.
- **Buffer reserves**: creating buffer reserves within carbon sequestration projects to ensure a portion of carbon offsets or captured carbon remains untapped as a safeguard against unexpected reversals.
- **Insurance and risk management**: investing in insurance mechanisms and carbon risk management funds to address financial losses and ensure continued compliance with the climate neutrality target if reversals occur.
- **Durability enhancement**: prioritising the integration of carbon capture technologies into infrastructure projects to store carbon permanently.

By implementing this multi-faceted strategy, Greater Dunkirk aims to strengthen its overall approach to achieving long-term climate neutrality.

Potential side effects need to be fully considered by cities before the adoption of any CDR, based on the best available information and research advancements at the time of planning (and/or implementation). While CDRs have some potential to deliver win-win solutions for sustainability, trade-offs cannot be ruled out. According to the Carbon Removal and Carbon Farming Regulation (European Parliament and Council, 2024b), "it is appropriate to establish minimum sustainability requirements to ensure that those activities do no significant harm to the environment and are able to generate co-benefits […] Those minimum sustainability requirements should take into account the impact of the activity both within and outside the Union as well as local conditions, and, where appropriate, be consistent with the technical screening criteria for the 'do no significant harm' principle, and be in line with the sustainability and greenhouse gas emissions saving criteria for forest and agriculture biomass raw material laid down in Directive (EU) 2018/2001. Practices that produce harmful effects on biodiversity, such as forest monocultures producing harmful effects on biodiversity, should not be eligible for certification."

Potential adverse impacts shall be accounted for. For instance, the GHG emissions associated with transport or maintenance operations may shift the overall benefit and there may be spillover effects to consider across different GHGs. This might be the case of wetland restoration, an efficient CDR option, but also a source of methane. Given the high warming potential of $CH_4$ relative to $CO_2$, some restored wetlands could need up to a century to balance $CO_2$ uptake and methane release, and thus become net GHG sinks (EPRS, 2021). This may be hard to achieve within the Cities Mission timeline. Furthermore, some undesired impacts arise depending on where and how compensation strategies are implemented. For instance, planting forests in snow-covered boreal areas and spreading biochar on soils can reduce the local albedo[8] and, therefore, enhance local or regional-scale warming (Perugini et al., 2017). When the albedo is significantly lowered, higher surface temperatures may cancel out or reverse the net positive impact on GHG emissions (typically observed at scales larger than urban scale). A non-exhaustive overview of how different CDR options may trigger potential detrimental effects on sustainability and acceptability in urban settings is provided in **Table 5**, based on recent scientific literature on the topic. These effects mostly refer to large-scale deployment of CDRs. Implications of CDR are highly context and setup specific and may be positive or negative, depending on how CDR is implemented.

**Table 5**. Overview of positive and negative CDR impact categories connected to environmental integrity and their relevance in urban contexts. The overview of impact categories and related CDR options is not conclusive but rather informed by recent literature evidence (Prütz et al., 2024; Rodriguez Mendez et al., 2024). AR: Afforestation and Reforestation. EW: Enhanced Weathering. SCS: Soil Carbon Sequestration.

| Impact category | CDR options | Examples of positive/negative impacts in the urban context |
|---|---|---|
| Air quality & condition | BioCCS, Biochar, DACCS, EW | Some CDR options may adversely affect air quality, e.g., by increasing the formation of particulate matter or photochemical ozone. Urban vegetation could however be a key ecosystem service for mitigating air pollution, while BioCCS technology on waste incineration plants mitigates the release of pollutants including carbon dioxide, nitrogen oxides, sulfur oxides, and particulate matter. |
| Biodiversity | AR, BioCCS | CDR-related land use change may adversely affect urban habitats for biodiversity. Indirect biodiversity impacts might also occur outside urban areas, e.g., in the forests sourcing biomass-based construction materials for urban environments. However, depending on how it is implemented, CDR options such as afforestation or revegetation may also contribute to habitat conservation and improve the conditions for urban biodiversity. |
| Energy | DACCS, EW | Deployment of DACCS or enhanced weathering may substantially increase urban energy demand with indirect impacts on prices or emissions for energy production within or outside of the cities' boundaries. Under specific conditions, DACCS can improve the business case for renewable energy deployment by ensuring stable demand, with excess energy available for other purposes, such as local industrial activity. Other CDR options, such as BioCCS, or biochar may produce energy as a co-product. Urban vegetation could also incur building energy savings from vegetative cooling and tree shading, while potentially increasing emissions from maintenance and irrigation. |
| Food & Yield | AR, BioCCS | CDR, especially land-intensive options such as afforestation and BioCCS, may affect urban food production due to land competition. Meanwhile, CDR options such as biochar or soil carbon sequestration may improve soil health on urban cropland, potentially supporting yield increases. |
| Heavy metals | Biochar | Some CDR options, such as biochar, may affect the natural cycling of heavy metals with positive or negative impacts for urban soil health and water. Biochar can also be used for the remediation of heavy metals in soil. |

[8] The albedo is the fraction of sunlight (solar radiation) reflected by a surface.

| | | |
|---|---|---|
| Land use | AR, BioCCS | Afforestation and BioCCS are very land-intensive CDR options, which may further increase competition for land in urban areas. CDR-related land use change may result in indirect implications for other impact categories such as biodiversity conservation or food production. |
| Non-$CO_2$ GHGs | Biochar, SCS | CDR deployment may trigger or reduce non-$CO_2$ GHG emissions, particularly methane and nitrous oxide emissions from soils, which may partially offset or even increase CDRs' contribution to achieving net-zero emissions. |
| Nutrients & minerals | AR, BioCCS, Biochar, EW, SCS | Several CDR options may influence nutrient and mineral stocks – especially nitrogen, phosphorus, potassium, and related compounds – in plants and soils and alter their leaching into urban freshwater. |
| pH change | AR, BioCCS, Biochar | Some CDR options, especially options using biomass as feedstock, may alter pH in soil and water bodies, potentially triggering or reducing acidification. |
| Raw materials | BioCCS, Biochar, DACCS, EW | To scale up CDR, cities shall prepare for changes in supply chains and material demand, e.g., for biomass, sorbents, and silicates, cement, clay, steel, and sand. Changes to material demand may also affect commodity prices. |
| Soil condition | AR, BioCCS, Biochar, SCS | Several effect categories such as changes to pH or the cycling of water, nutrients, and heavy metals may impact the condition of urban soils. Biochar, and SCS may on the other hand increase soil fertility. |
| Thermal impact | AR, BioCCS, Biochar, SCS | Depending on the CDR option and mode of implementation, CDR may have a biophysical warming (e.g., through increasing albedo) or cooling (e.g., through plant evapotranspiration and tree shading) effect. If properly implemented, such effects may be used to mitigate urban heat island effects. |
| Toxicity & radiation | BioCCS, Biochar, DACCS | Freshwater, and terrestrial ecotoxicity of CDR options need to be considered to ensure safe deployment in urban context. |
| Water cycle | AR, BioCCS, Biochar, DACCS | Some CDR options are characterized by high water demand, which may add stress to urban water systems. At the same time, CDR deployment may positively or negatively affect runoff and drainage, which is important for urban flood management. For instance, depending on the mode of implementation, urban vegetation and biochar can provide stormwater management services. |

*Source: JRC analysis.*

In addition to biophysical integrity, urban CDR and greening measures shall respect social and climate justice principles. Ethical analyses stress that large-scale, land-based CDR should avoid externalising burdens onto vulnerable communities through land competition, water stress and forced displacement, especially in already marginalised regions (Schübel et al., 2025; Voget-Kleschin et al., 2024). Evidence from multiple cities shows that new parks, trees and other green infrastructures can catalyse "green" (climate) gentrification, whereby environmental improvements increase property values and contribute to the displacement or exclusion of low-income and racialised residents, unless strong anti-displacement and equity-oriented governance measures are adopted (Anguelovski et al., 2022; Cucca & Thaler, 2023). However, urban greening can also increase the recreational value of public spaces and improve mental health by giving citizens access to nature, reducing stress, and fostering social connection. CDR policies that rely on land-intensive options or price agricultural emissions can affect agricultural markets, food prices and rural livelihoods: competition for land and higher production costs are projected to increase food prices, raise the risk of hunger and impose regressive welfare losses on low-income and rural households, while also reshaping jobs and value chains in agriculture. Multi-model assessments show that ambitious afforestation or carbon pricing on land carbon stocks can put tens of millions more people at risk of hunger by 2050, primarily via higher food prices and reduced food consumption in poorer regions (Fujimori et al., 2022; Kreidenweis et al., 2016). Aggressive forest carbon sequestration subsidies similarly induce substantial food price increases, especially when combined with climate-induced yield losses, to levels judged politically and socially unfeasible (Peña-Lévano et al., 2019). Compensating for unabated agricultural non-$CO_2$ emissions with CDR and passing those costs onto food commodities can increase retail prices for key staples and animal products (e.g. beef, milk, rice) by up to 40% or more, disproportionately burdening low-income households who spend a larger share of income on food and exacerbating poverty risks (Brazzola et al., 2021).

Carbon pricing applied directly to agriculture (including non-$CO_2$ emissions and inputs like fertiliser) raises production costs and consumer prices, with poorest rural households experiencing the largest welfare and nutrition losses (Adenauer et al., 2025; Jensen et al., 2019; Pieralli et al., 2025; Q. Zhang et al., 2024). At the same time, producers may see mixed effects on profitability and output, with implications for employment and structural change in agricultural sectors. On the other hand, urban CDR and related $CO_2$-utilisation industries can create new jobs in project development, engineering, monitoring and verification, construction, and in novel $CO_2$-based manufacturing processes and land-based sectors if policies actively support worker retraining and just transitions (Edenhofer et al., 2025; Honegger et al., 2021; Warsi et al., 2020) (see **Section 6.4** for a broader discussion on the co-benefits of CDR). The fact that current CDR-related concerns mostly arise when large-scale implementation is concerned, reinforces the need to abide by the Emissions Reduction First Principle and the Diversification Principle (see **Section 6.5**) to avoid CDR oversizing. Large-scale CDR can be pursued for its potential to compensate for a large share, if not all, of residual emissions and potentially contribute to net-negative emissions, but should be carefully conceived, tested and monitored. An iterative approach to CDR deployment with adequate and transparent review mechanisms would allow for continuous learning, improvement, and adaptation as the field evolves.

When dealing with carbon credits intended to count toward climate neutrality targets, the Environmental and Ethical Integrity Principle largely translates into ensuring that credits are **certified carbon removals**, in line with the CRCF's quality and monitoring requirements (European Parliament and Council, 2024b). Not all carbon credits currently available in the voluntary market meet those criteria. In general, the environmental integrity attributes outlined in **Table 4** shall be demonstrated. Risks of fraud and double counting should be dispelled transparently to ensure that only one carbon credit is associated with a single removal of 1 $tCO_2$ and no double counting between projects or governmental GHG accounts occurs (**Box 21**).

Given the evolving state of voluntary markets and the upcoming implementation of CRCF certification bodies and registries, cities should carefully assess the credibility and traceability of projects they invest in or purchase credits from and prioritise partnerships that demonstrate alignment with EU requirements. In general, priority should be given to projects with a long track record in additionality and quality, which have demonstrated, on many occasions, to have no detrimental impact on the environment or on society. Additionality can be difficult to determine and verify, and ultimately involves some degree of subjectivity since the counterfactual world in which the offsetting activity is not performed cannot be observed directly (M. Allen et al., 2020). In view of reaching climate neutrality the minimisation of any potential leakage is also critical[9]. Leakage can be mitigated by including all significant in-boundary and out-of-boundary emissions that occur as a consequence of the credit-generating activity or by designing appropriate precautions and interventions in sectors or sub-sectors affected by leakage. Emissions should not be merely displaced and/or aggravated elsewhere. To identify and estimate sources of leakage associated with specific climate mitigation policies and actions, cities may refer to the GHG Protocol Policy and Action Standard (WRI, 2014).

[9] To identify and estimate sources of leakage associated with specific mitigation policies and actions, users could refer to the GHG Protocol Policy and Action Standard.

**Box 19.** Risk of fraud and double counting

When the "unambiguously owned" and "transparent" attributes of carbon crediting are not respected, there is a risk of fraud and double counting, since:

— The same carbon credit may be claimed by two different jurisdictions and applied by both towards their mitigation targets.

— The same carbon credit or the same proportion of a carbon credit (in case of shared credits) may be claimed by both seller and buyer and applied toward the mitigation target of both.

— The same carbon credit may be sold twice (double selling). This may occur as a consequence of a fraud whereby more than one credit is issued for the same project because the project has been registered under two different certification schemes or has been registered twice under the same scheme.

— More than one credit may be generated for 1 unit of emission reduction (double issuance).

— The same credit is used several times to make the same claim (fraud).

To prevent fraud and double counting, a number of mechanisms to track units and enforce non-duplicate claims among buyers and sellers should be arranged (Levin et al., 2014):

— A registry that lists the quantity, status (cancelled, retired, or banked), ownership, location, and origin of carbon credits.

— A transaction log or blockchain that records the details of each transaction between registry accounts, including the issuance, holding, transfer, and acquisition of carbon credits.

— Agreements between buyers and sellers that specify which party has the exclusive right to claim each credit and specifies what percentage, if any, is shared.

— Legal mandates that disallow double counting and employ penalty and enforcement systems.

— Information sharing to identify credits that are already registered in other programmes.

Registries and tracking systems should be interoperable, publicly available, and in electronic form. They should be set up in a way that ensures cities can understand offsetting activities at different levels within the city (e.g., by private companies or individuals), providing clarification in terms of how those activities have/have not been, or should/should not be factored into the city's emissions inventory. Mission Cities are encouraged to pursue transparency and full disclosure whenever possible, as this would reinforce the commitment taken with citizens and stakeholders in signing the CCC.

Overall, local acceptance of in-boundary CDR and carbon credits is not only conditional on transparent governance (see **Box 18**) and robust monitoring (see **Box 5**) but also on its environmental and ethical integrity (e.g., fair distribution of risks and benefits, credible remediation plans). Projects may be rejected when local communities perceive asymmetries between local environmental burdens and benefits accruing elsewhere (O'Sullivan et al., 2025). Defining which pathways are most compatible with environmental protection, sustainable development, and human rights (Lenzi et al., 2018) requires a city-specific analysis of contributing factors (demographic, economic, cultural, political, technological, environmental, and infrastructural factors, see for instance **Box 20**).

**Box 20.** Strategic and equitable utilisation of out-of-boundary sinks

When considering the use of carbon sinks, such as forests, beyond the target boundary, it is recommended to take a holistic approach that balances local needs with broader regional and social implications. Key questions include:

— Is there a risk of depleting the carbon removal potential of a geographical area serving a wider population?
— Is a transboundary approach hindering others' ability to contribute to and achieve their share of climate neutrality goals?

When utilising carbon sequestration potential from beyond the target boundary, it is important to consider the broader implications on long-term climate neutrality and equitable resource distribution. Adopting a per capita fair share principle could ensure equitable distribution of resources, preserving the potential for achieving larger-scale climate neutrality and supporting the long-term sustainability of climate action plans.

**City in the spotlight: Helsinki (Finland)**

Helsinki is currently working on three technical reports to guide the delineation of its residual emissions strategy (Helsinki, 2025). These reports, focusing on carbon sinks and compensation challenges, will undergo political review to inform decision-making. The city is exploring emissions compensation options, such as enhancing carbon sinks within the city, all the while considering further reducing emissions, due to uncertainties in compensation regulations. Challenges include verifying potentials and avoiding double counting, particularly with actions in other regions. The financial implications of various solutions, such as investing in technical sinks like CCS/CCU, are significant, and the city is conducting cost-impact analyses to determine the most viable options. Helsinki is also leveraging innovative tools like the "Carbon Negative Helsinki" board game to raise awareness and understanding of a carbon-negative future as a way to probe and/or stimulate public acceptance around compensation of residual emissions. The city is also participating in projects that study and promote the use of biochar and is networking with other operators to stay up-to-date on the latest developments in this field.

Helsinki has incorporated adaptation measures into various programmes and developed tools, such as the stormwater programme, green roof guidelines, and the green factor tool. The city has updated its building regulations to include a lot-specific green area factor (which is now mandatory when applying for a construction permit, ensuring that new developments include sufficient green infrastructure). Within the ARVO project, partially funded by the EU, the city aims to expand the green area factor from individual lots to larger public areas.

## 6.4 Co-benefits and synergies

A guiding principle in selecting the methods and strategies to compensate for residual emissions is to prioritise technologies, techniques, and credit-generating projects that maximise the co-benefits in the local territory (and beyond) and the synergies with other city goals and action plans (**Box 21**). The CRCF framework requires that all certified activities do no significant harm. While mandating specific co-benefits for carbon farming activities related to biodiversity, ecosystems, and soil health, the CRCF allows for optional (voluntary) reporting of other co-benefits across all activity types (European Parliament and Council, 2024b). Only carbon farming projects are required to benefit the protection of biodiversity and ecosystems. Mission Cities are however advised to prioritise CDR

activities that maximise co-benefits across the whole spectrum of options. Co-benefits that align with the United Nations Sustainable Development Goals (SDGs) might be prioritised while specific standards that monitor CDR co-benefits like the Climate, Community & Biodiversity (CCB) Standards[10] can provide a useful reference and guidance for cities.

Critical co-benefits would be generated where compensation translates into restoring and expanding natural ecosystems such as forests and wetlands to capture and store carbon. Co-benefits include climate change mitigation and adaptation (**Box 22**); the protection and restoration of biodiversity and ecosystems, including soil health and avoidance of land degradation; the sustainable use and protection of water and marine resources; the transition to a circular economy, including the efficient use of sustainably sourced bio-based materials; and pollution prevention and control (European Parliament and Council, 2024b). An overview of co-benefits discussed in the scientific literature is given in **Table 5** in **Section 6.3**. Socio-economic co-benefits should also be considered (e.g., health, green jobs creation). On the other hand, carbon removals may themselves emerge as a co-benefit of actions primarily undertaken for other purposes.

Regardless, a positive balance between co-benefits and adverse impacts needs to be stricken and cross-sectoral considerations need to step in. This has implications on the MRV system in place. Taking tree planting as an example, when maximising negative emissions is the only objective, park-like design and maintenance is typically less effective than forest-like design and maintenance (Strohbach et al., 2012). However, capillary dissemination of green features serves critical climate adaptation purposes such as creating a cooler urban environment and countering heat island effects or increasing the city's resilience against heavy rainfall and flooding. This, in turn, generates a number of indirect benefits on climate mitigation. Further, when city surfaces are unsealed and greened or when building roofs and facades become green, direct emissions reductions are achieved in the stationary energy sector.

In the context of carbon credits, co-benefits might increase the value and potential market premium of the certified carbon removals, depending on the certification framework. For instance, the CRCF considers the generation and reporting of sustainability co-benefits as a value booster and encourages it through its design, certification methodologies, and reporting requirements (European Parliament and Council, 2024b). Cities taking a developer or investor role in carbon offsetting may be better positioned to ensure that greater co-benefits and better alignment with local priorities are delivered, as compared to cities purchasing credits available from externally developed projects. The credit's geographical sourcing can also be leveraged to pursue a more active role in reaping benefits for the city itself, its neighbouring areas, or its regional context.

Co-benefits can also be of socio-political/operational nature. Accordingly, this principle could translate in privileging options that:

[10] The CCB Standards are a set of voluntary standards used to evaluate land management projects that deliver net positive benefits for climate change mitigation, local communities, and biodiversity. Managed by Verra, these standards are specifically designed to be applied to land-based carbon projects, including those focused on carbon removal (e.g., afforestation, reforestation, revegetation, and agroforestry).

— **Better align with city cross-cutting priorities, national priorities and objectives, procurement requirements, and level of buy-in from local stakeholders**. This may speed up and maximise the rate of implementation, stimulate synergies and support broader national climate objectives.

— **Avoid perverse incentives.** This translates into avoiding vicious mechanisms whereby profitable international crediting markets encourage the absence of climate mitigation policies or regulations in host countries.

— **Promote climate solidarity**. In the context of carbon credits, projects in developing contexts could be prioritised in line with climate solidarity principles.

**Box 21.** Embedding CDR in urban policies and systems

CDR should not compete with existing urban policies but instead enhance them. By leveraging synergies with policies for public services concerning for example energy, waste, land use, food, wellbeing and urban planning, cities can:

— Enhance co-benefits across urban policies.

— Strengthen financial viability for CDR projects by tying them to essential services.

— Improve public engagement by positioning CDR as part of broader urban sustainability initiatives.

CDR can be integrated holistically into urban systems planning, urban infrastructure and governance structures. "Embedded CDR Policymaking" is a meaningful approach for cities that want to pursue a holistic integration of CDR. This policy approach has several benefits:

— **Minimising experienced costs**: Rather than purchasing CDR credits (often for hundreds of €/t$CO_2$, see **Box 23**), regulatory embedding is experienced as a modest cost increase to an existing activity (e.g., 0-5% increase in wastewater de-acidification costs), improving political stability of the policy.

— **Progressive cost re-distribution**: Any additional cost to remove carbon will be passed on in some way. By attaching that cost to specific regulated activities (e.g., data center construction & cooling, commercial property development, industrial wastewater treatment), municipal leaders may be able to better maintain public support.

— **Stabilised demand signal**: These policy tweaks provide a clear signal to city planners and contractors alike, justifying capital expenditures for CDR retrofits.

At the municipal level, several industrial processes are strong candidates for this approach, including but not limited to the management of construction and building demolition waste, and municipal wastewater treatment. Cities with ambitious net-zero goals may be able to leverage their already-established permitting infrastructure to, for example, require that an escalating percentage of concrete waste be "re-carbonated" (crushed and reacted with atmospheric or biogenic $CO_2$) before it is either land-filled or recycled. Likewise, existing permitting schemes for wastewater effluent may specify acidity, nitrogen and phosphorus levels for water that is returned to rivers following treatment; tweaking these specs can directly drive the uptake of non-toxic alternative materials, such as limestone, which could deliver better environmental outcomes while also removing carbon.

In these examples, cities sidestep the need to rely solely on variable and inconsistent corporate demand for carbon credits, opting instead to require a predictable volume of carbon removal within select industries. Corporate VCM demand can be funneled toward otherwise un-financeable CDR methods (e.g., direct air capture), while municipal rule setting can bake in the motivation to remove carbon for other methods (including the aforementioned "wastewater liming" and "building demolition waste recarbonation"). Since municipal and regional permitting schemes shall already adhere to EU-wide quality floor regulations such as the Urban Wastewater Treatment Directive (European Parliament and the Council, 2024a), the

embedded CDR policy approach gives cities a way to go above and beyond and act as leaders, piloting new technologies and approaches before their peers that can help draw talent, funding, and reputational benefits to their city.

**Cities in the spotlight: Munich (Germany)**

In the Expression of Interest, the city of Munich showed proactivity in sustaining local co-benefits within its residual emissions strategy. In case net-zero GHG emissions cannot be completely reached by 2030 within the city boundaries, the city prefers to realise and fund regional carbon sink projects in the wide Munich Metropolitan area instead of offsetting emissions elsewhere. The city highlights that the restoration and rehydration of wetlands has great potential in Bavaria, thus a pilot project is anticipated, led by the city forestry administration.

As the embedment of the Co-benefits principle in the residual emissions strategy may not be easy to verify, cities are encouraged to disclose in their CNAP i) the policies and measures to tackle potential trade-offs and fully abide by the "do no significant harm" principle, ii) the synergies between climate mitigation and adaptation (incl. policies and measures to reduce the vulnerability of land to natural disturbances and the climate); and iii) the synergies between climate mitigation and biodiversity. This is in line with what Member States are to include in their compliance report to the amended LULUCF Regulation (European Parliament and Council, 2023b) – see **Section 9**.

**Box 22.** Carbon removal synergies with climate adaptation

Research into the carbon removal-climate adaptation nexus is still in an early stage, despite the presence of many potential ways to foreground carbon removal in climate change adaptation policies and project designs to maximise the impact of public interventions.

When speaking about climate adaptation, we use the IPCC's definition which refers to "the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects". Adaptive capacity is "the ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences" (IPCC, 2018c). Building on such definitions, Buck et al. developed the concept of 'adaptive carbon removal' connecting both instruments. It refers to practices that remove carbon from the atmosphere while also providing benefits to human and natural systems in the face of climate change impacts (Buck et al., 2020).

As it stands, there is no analytical framework that allows for a systematic evaluation of the interplay between carbon removal and climate change adaptation. There are some areas of research that touch on the nexus as a side issue or in an implied way. For instance, researchers focussed on 'ecosystem based adaptation' have noted that the associated policy mix "links policies related to BES (biodiversity and ecosystem services), socio-economics and carbon mitigation, and can be an important driver of adaptive transitions" (Scarano, 2017). Other discussions revolve around how certain co-benefits generated by carbon removal methods can strengthen the "demand-pull" for new methods by offering entry-points for public policy support (Cox & Edwards, 2019). Both approaches offer promising avenues for connecting carbon removal with adaptation in practice.

The potential for carbon removal interventions to increase adaptive capacity is however highly context-dependent and does not flow inherently from the CDR method itself. The synergistic effects of integrating carbon removal interventions into adaptation policies and project designs can also be justified by focusing on enhanced sink capacity, assuming that the integration does not reduce the impact of the adaptation measure. Many carbon removal interventions do not hold the potential or cannot guarantee an increased

adaptation capacity, while badly designed integration may even lead to a reduced adaptation capacity, also known as maladaptive instances of carbon removal (Buck et al., 2020). Since this is already a risk for adaptation activities in and of themselves (Sovacool, 2018), there is no reason to believe that this does not hold true for coupling removal with adaptation activities.

Cities are advised to consider the potential for carbon removal integration when designing climate adaptation policies and project designs. Across the landscape of CDR methods, there are many project types that simultaneously remove carbon and lead to GHG reductions, climate adaptation, biodiversity improvement, air pollution reduction, soil quality improvement, or enable other socio-economic benefits, such as local industrialisation, new municipal revenue sources and investment streams, and talent attraction. Adaptation is one of the most promising cross-policy synergy for carbon removal. Possible synergies with adaptation include:

— Heat stress: shade increases with urban forest coverage that also creates sinks to sequester $CO_2$.

— Water stress: water retention improves with regenerative agriculture practices that also sequester $CO_2$.

— Coastal erosion: coastal fortification with bulk materials and enhanced rock weathering can also permanently sequester $CO_2$.

— Flooding: flood protection with wetland restoration can enhance carbon sinks.

— Ocean acidification: adding alkaline substances to seawater that counters acidification creates bicarbonates and carbonates that permanently store $CO_2$.

— Soil depletion: adding biochar to land to increase soil fertility and soil moisture can permanently sequester $CO_2$.

A cautious approach is warranted. Buck et al. analysed four case studies of adaptation projects that included carbon removal elements and found that the design of adaptive carbon removal projects and policies should place local ecological conditions at its centre to maximise adaptation benefits (Buck et al., 2020). New policies are needed to explicitly promote the realisation of the synergies, but consistency of policy is important where the success of projects relies on financial incentives. On top of this, when there is a variety of carbon-negative options that connect with a particular adaptation need, the one that sequesters the most $CO_2$ does not necessarily have the greatest adaptation effect.

In line with these findings, the researchers propose three principles for integrating carbon removal and adaptation effectively (Buck et al., 2020):

— Identify carbon-negative opportunities when designing responses to adaptation needs.

— Prioritise adaptive value in choosing and designing projects over realising carbon removal when the main objective is to address climate adaptation needs.

— Recognise communities and cities that implement carbon-negative adaptation measures and allocate value to carbon removal, such as in incentives or policy compliance.

## 6.5 Diversification

The Diversification Principle is a key ally in the design of residual emissions strategies that are more robust and exhibit a lower-risk profile (hence, more environmentally and financially attractive). Diversified strategies protect against the failure of individual practices, as the overall risk is distributed. This Principle applies not just across macro-categories of compensation mechanisms (e.g., temporary carbon removals, permanent carbon removals, and carbon credits), but also within the same categories.

In the context of nature-based carbon sinks, a mix of options that leverage the urban, periurban, and rural landscapes in cities and designed to deliver energy, economic, and societal co-benefits determines a deeper physical transformation and a reduced risk of significant and synchronous reversals. In particular, applying the Diversification Principle in the context of forestation programmes translates into a higher carbon removal potential and longer lasting effects (see **Box 32**). Different tree species and different tree ages enhance the compositional diversity of urban forests and result in a more stable carbon storage capacity.

In the context of permanent removals, the combination of several options can avoid the constraints of large-scale deployment of any one technology (Peters, 2016). Diversification also means resource protection. For instance, a widespread deployment of BioCCS to meet the 1.5 °C climate target would almost double the anthropogenic water footprint (Rosa et al., 2021). This would likely exacerbate and create green and blue water scarcity conditions in many regions worldwide. Climate-neutral pathways with a diversified portfolio of CDR technologies have lower impacts on water resources than scenarios relying mainly on one of them (Rosa et al., 2021). Similar considerations apply to land and energy resources.

Finally, when in-boundary carbon removals are complemented with out-of-boundary carbon credits, it is advisable to rely on a portfolio of credit-generating projects to distribute the overall risk and take different roles (developer, investor, or buyer) to distribute the overall responsibility. Different projects have their distinct pros and cons, but a mix of credits across different projects, geographies and standards can i) achieve multiple objectives (i.e., carbon removal, avoidance, destruction, or reduction), ii) better handle permanence (by making sure the strategy does not rely only on short-lived storage), iii) hedge against market fluctuations, regulatory changes, and potential supply shortages, iv) combine new methodologies (that typically exhibit higher potential yet also higher costs and risks) with better established practices, and v) deliver immediate impact (by leveraging ex-post carbon credits). This diversification helps to make offsetting stable and affordable so that cities are not forced into simply opting for the cheapest solution but can more comfortably venture in more ambitious projects.

**City in the spotlight: Differdange (Luxembourg)**

Differdange's strategy for addressing residual emissions embeds the Diversification Principle by combining temporary removals, permanent removals, and carbon credit purchases (Differdange, 2025). Further, it includes local and international initiatives to reduce emissions and enhance sustainability. Locally, it promotes urban afforestation and revegetation and mandates carbon-capture construction materials ($CO_2$-infused concrete, certified timber) via regulatory reforms. The city also sells municipal carbon certificates and supports regional projects like habitat restoration and reforestation. Internationally, Differdange collaborates on CCS/CCU projects in the Netherlands and Norway and purchases international offset certificates. Initiatives include promoting green public spaces, forest bathing, green roofs, agroforestry, supporting local farmers, and exploring carbon capture and storage solutions. The city also plans to integrate $CO_2$ storage in concrete and wood into municipal tender dossiers, and to create a municipal system for the sale of local $CO_2$ storage certificates. Notably, the DiffPrimes project aims to increase the number of fruit trees in the city and promote green facades for 500 buildings, focusing on capturing greenhouse gases through tree growth and establishing a recognised supply chain for green products. The project involves various initiatives, including collaborations with local stakeholders, feasibility studies, and the use of innovative materials like carbon-captured concrete and CCU wood, with the goal of increasing carbon compensation in construction and promoting sustainable development. The city is also considering the use of hybrid Paulownia trees for carbon capture and the development of a natural insulation production chain using local materials. The city's collaboration with the Luxembourg Institute of Science and Technology and ArcelorMittal to explore CCS solutions also demonstrates its commitment to innovative

compensation measures. The promotion of forest bathing and the creation of "instagrammable" places in the forest are also creative approaches to raise public awareness of environmental issues related to urban planning and carbon sinks protection.

## 6.6 Cost and time effectiveness

Cities operate under different social, political, and economic constraints, priorities, interests, and possibilities. These differences may play a role in the economic viability and timing for use of compensation mechanisms.

Concerning costs, an open-source, searchable database of EU funding opportunities for CDR was created in 2025 (Carbon Gap, n.d.). The goal of the database is to help decision makers, researchers, funders and other CDR stakeholders in making informed decisions about CDR funding. Mission Cities can benefit from the database to conceive the funding approach to their residual emissions strategy. The database is regularly updated. It allows for browsing public funding for carbon removal in Europe by identifying grants, incentives, and support schemes by country or at EU level, funding type or storage method.

However, tapping into private financing would be crucial to unlock the investment volume required for a diversified compensation strategy covering all residual emissions. A range of climate finance instruments can be used to support urban CDR development. Some instruments may be more appropriate for certain CDR methods than others (Gevers Deynoot et al., 2025). A diversified funding strategy that takes this diversity into account and relies on a variety of funding sources reduces risk and uncertainty over time. In general, it is important that cities move beyond dependence on volatile voluntary carbon market demand to fund the implementation of their residual emissions strategies.

In the context of carbon credits, the capital costs applicable to the project developer and the credit buyer should be compared. The cost-effectiveness and the role definition also depend on the level of experience and capacity of the city in developing, monitoring, or assessing carbon credit projects. Less experienced cities may rely more heavily on outsourcing and this may constitute a significant cost difference between developer and buyer roles.

Concerning timing, a late or early compensation of residual emissions may unlock different potential advantages and disadvantages, whose likelihood and impact may vary from city to city. **Table 6** provides a non-exhaustive list of factors and avenues to consider when assessing different timing approaches. This kind of considerations should guide the decision-making process already at the time of compiling the CCC for Mission Cities.

**Table 6**. Potential advantages and disadvantages of late and early compensation of residual emissions, for Mission Cities.

| **Potential advantages** | **Potential disadvantages** |
|---|---|
| **Late Compensation – close to 2030** | |
| Focus on emissions reduction at source until close to 2030. Cities would have more chances to reduce their emissions (with all co-benefits in the local area) and minimise removals/credits oversizing. | Higher risk of not fulfilling the climate neutrality ambition by 2030. Taking late action on residual emissions poses challenges in reaching net-zero on time, notably if setbacks are encountered in the design and/or implementation of compensation measures and especially when natural sinks are concerned (given the typical time scale to achieve the intended sequestration potential). |

| | |
|---|---|
| Technological advancements may enable further abatement of sources for which GHG emissions reductions are currently economically or technically unfeasible. Piloting and testing new technologies could be an economic incentive for the local industry. | Higher uncertainty on costs and regulation. |
| More time and opportunities to steer peer-to-peer learning and capitalise on shared experiences and other cities' lessons. This may include the launch of dedicated projects and pilot demonstrations, depending on the level of maturity required to enhance emissions reduction at source. | Higher uncertainty on availability of carbon removal or carbon storage projects and on residual global carbon budget in the future. |
| Reduced uncertainty over feasibility, risks, and trade-offs of compensation mechanisms, notably technological carbon sinks. Further, stakeholders may have more opportunities to fine tune responsibilities and avoid hiccups/failures in implementation. | Cities bound by stricter timelines may be more inclined to purchase – rather than develop or invest in – carbon credits. This may translate into limited contribution to the local (environmental, economic, social) prosperity as the co-benefits associated with the project would be typically distributed elsewhere. |
| More time to conduct thorough assessments of all direct and indirect environmental, social and ethical impacts of compensation strategies, to prevent or mitigate potential adverse effects. | |
| **Early Compensation** | |
| On-time appreciation of effects. There may be a time lag between potential initial increase in emissions and removal (e.g., trees need to reach a certain maturity to develop their carbon sequestration potential). Taking an early action increases the chances that the negative emissions potential is enjoyed by 2030. This is particularly relevant when the land sector is concerned. | Ethical, political and consensus concerns from perceived undercommitment or irresponsibility in strategic thinking. There is a higher risk, especially in case of substantial residual emissions and/or failures in implementation, that the time and economic effort put into compensation techniques and technologies are seen as a premature diversion of resources from emissions reduction at source, with serious consequences for future generations. |
| Greater time buffer to deal with potential setbacks, to perform tests and pilots before large-scale implementation, and to design a long-term strategy. | Higher risks in implementation, in contexts of limited prior experimentation. With the increment in net-zero commitments at multiple governance levels, it may be expected that numerous compensation strategies will be tested in the coming years. This knowledge and know-how could better serve cities opting for a late compensation strategy. |
| The time horizon available for offsetting projects gives the city more freedom to choose its role, possibly in view of guaranteeing better adequacy to the local environment and greater co-benefits. Cities taking an early compensation strategy may be more inclined to develop or invest in (rather than purchase) carbon credit projects with the possibility to select projects that respond more closely to local necessities and priorities. | Potential higher investment. Technological breakthroughs over time may increase the affordability and improve the risk profile of compensation strategies. Early action of non-mature technologies may result in very high upfront costs and very high uncertainty on the return of investment. |
| Leadership and business. Cities that take an early action in delivering compensation means, may act as pioneers and establish profitable activities around voluntary carbon markets, especially when negative emissions exceed residual emissions. Cities piloting CRCF-aligned projects early could shape EU standards & secure funding/preferential treatment. | Higher risk of investment in carbon projects that may not be certifiable under EU frameworks, such as CRCF. Waiting may allow access to certified removals that fully meet the CRCF requirements as methodologies and registries mature. |

*Source: JRC analysis.*

While the above considerations apply to both in-boundary carbon removals and out-of-boundary carbon credits, when dealing with credits, cost and time effectiveness largely depend on the option(s) elected by cities: spot purchase, forward purchase, multi-year purchase, and investment. Definitions, potential advantages, and potential disadvantages are condensed in **Table 7**.

**Table 7**. Potential advantages and disadvantages of carbon credit purchases with different temporal horizons (Lune, n.d.).

| Potential advantages | Potential disadvantages |
|---|---|
| **Spot purchase**: carbon credits are bought and sold with immediate and full payment, delivery, and retirement based on current market price | |
| Secured price of carbon credits | Uncertainty in future budget planning due to potential fluctuations in carbon credit prices, which may necessitate re-budgeting for repeated purchases in subsequent years. |
| Assurance of carbon credit supply | Potential supply constraints for large-scale carbon credit purchases, as the availability of projects offering sufficient ex-post credits to meet offsetting requirements may be limited. |
| Verified and guaranteed impact (immediate credit retirement) | |
| **Forward purchase**: the price for a set amount of carbon credits is agreed upfront, the buyer pays fully or partly at the point of purchase, and the credits are delivered and retired at an agreed future date. | |
| No anticipated supply constraints, with expected access to an increased availability of carbon credits in the future. | Delivery risk: since the carbon credits have not yet been generated, there is a risk that the project may not achieve its expected emissions removals, resulting in non-delivery of the credits. |
| Price certainty: the pre-agreed purchase price of carbon credits is guaranteed, protecting against potential price increases at the time of delivery and retirement. | Price risk: there is a possibility of overpaying for carbon credits if their market price decreases between the time of purchase and retirement, resulting in a less favourable deal. |
| Opportunity to support pioneering projects: forward purchasing enables access to innovative, high-potential carbon projects that may not have credits available for immediate sale, but can offer credits in the future. | |
| **Multi-year purchase**: the price for an ongoing annual purchase of carbon credits is agreed upfront, and the credits are delivered and/or retired at an agreed date each year. | |
| All potential advantages of forward purchases. | All potential disadvantages of forward purchases |
| Budget certainty: locking in carbon credit prices provides clarity on future costs, enabling more accurate budget planning and reducing financial uncertainty for the next few years. | |
| Deeper project engagement: entering into a long-term purchasing agreement fosters a strong partnership with the project developer, enabling collaborative opportunities such as joint marketing initiatives, site visits, and storytelling, which can enhance stakeholder engagement. | |
| **Investment**: upfront financing is delivered for the setup and/or development of a carbon credit project. | |
| Exclusivity or priority: investing in a project can secure a guaranteed allocation of credits at a potentially discounted rate, providing a cost-effective and reliable source of offsets. | Risk that credits cannot be delivered as for forward and multi-year purchases. |
| Project developer relationship and storytelling, even stronger than that achievable through a multi-year purchase, since the city is effectively enabling the project's existence. | Higher uncertainty on time of delivery/retirement. |
| Business opportunity: investing in a project can provide access to carbon credits at a lower cost, creating an opportunity for the city to resell them at a higher market price, generating a profit once the credits are issued and delivered. | |

*Source: JRC analysis.*

Forward purchases and investments can support the development of CRCF- and Cities Mission-aligned projects, however ex post verification is needed. This means cities cannot claim removals before they are

delivered and verified. Generally, spot purchases are ideal in case of one-off small purchases, where forward budget planning is not a concern, while multi-year purchases and investments are suited to large purchases, delivered in batches. As the voluntary carbon market is still in its infancy, investments as well as forward and multi-year purchasing may grant access to a larger and wider supply of carbon credits and may fund high potential, early-stage projects and enable them at scale; however, their projection into the future sheds uncertainty on credits availability and effective impact at the time of delivery/retirement.

Once a city has determined its timing and volume strategy, it should select the most appropriate purchasing channel. For smaller volumes or pilot initiatives, cities can purchase credits directly from online retailers or marketplaces. These platforms offer immediate access to certified units (e.g., Gold Standard) but often come at a premium and with limited support. For larger volumes, which is more typical for city-wide compensation strategies, purchasing through specialised intermediaries or brokerages is often recommended. These services can negotiate lower prices, handle registry accounts, and manage the technical retirement of units on the city's behalf. Finally, as presented above, cities seeking maximum strategic alignment and cost control may engage directly with project developers for their purchases. This can take the form of direct one-off purchases, long-term offtake agreements (contracts for future delivery), or even direct equity investment in new projects. While this direct approach requires significant internal capacity and due diligence, it offers the highest transparency and the potential to secure future supply at fixed prices.

**Box 23.** Understanding carbon credits prices

The price of carbon credits can vary significantly, ranging from a few euros to several hundred euros per $tCO_2$. While there is some correlation between price and credit quality, quality is not the only contributing factor. The value and cost of a credit are influenced by a dynamic combination of market forces, project characteristics, and broader regulatory factors.

Key factors determining the price of carbon credits include:

- **Supply and demand**: like any market, the availability of credits and the demand from companies and individuals heavily influence pricing.
- **Project type and technology**: different project types, such as nature-based projects (e.g., forestry) or innovative technological removals (e.g., DACCS), have varying implementation costs, which directly affect their credit price.
- **Project location**: some locations are more expensive to establish and run projects in, which can impact the price.
- **Standards applied**: high-quality projects that adhere to stringent standards generally command higher prices.
- **Co-benefits created**: projects offering significant social or environmental co-benefits (e.g., protecting biodiversity, empowering local communities) also tend to come with a premium.
- **Project size**: projects that generate a higher number of credits tend to profit from economies of scale, which can influence price.
- **Purchasing arrangement**: pricing can vary depending on the terms of the offtake agreement and contracting structure.
- **Vintage**: the year a credit was generated can affect its value, with newer credits often being more desirable.

Ultimately, prices vary significantly by project and are expected to change over time. For instance, prices for nature-based removals are expected to increase. Conversely, technological removal prices may stabilise or potentially decrease as the technology matures and scales, influenced by factors like location and public

subsidies (South Pole, 2025b). For informational purposes only, South Pole internal data as of 31 December 2025 suggest the following indicative prices for selected removal carbon projects:

— **NBS removals (afforestation, reforestation, revegetation, and improved forest management)**: 10-60 €/$tCO_2$.

— **Biochar**: 100-250 €/$tCO_2$.

— **BioCCS**: 250-450 €/$tCO_2$.

— **DACCS**: 450-1000 €/$tCO_2$.

# 7 Negative emissions accounting

As customary in climate mitigation, all actions taken to reduce (and in this case remove) emissions have to be confronted against a baseline that describes the status quo before the actions were undertaken.

Establishing a baseline means quantifying both positive and negative emissions (as well as sold or retired credits) associated with all sectors, sources, gases, and geographical areas included in the corrected target boundary. This entails, for instance, that where a city plans to resort to forestation or wetlands restoration to compensate for (a share of) its residual emissions, it should first appraise the current state of forests/wetlands and their associated GHG emissions and removals. According to the inventory data provided by 362 cities in their Expressions of Interest in the Cities Mission, the proportion of cities currently accounting for sectors where negative emissions occur (i.e., AFOLU) is limited; however, the vast majority of the residual emissions strategies foresee forestation or revegetation programmes. As such, a high percentage of Mission Cities will have to compile a baseline inventory for the AFOLU sector and any activity they intend to leverage to produce negative emissions. This may constitute a data-intensive and uncertainty-affected step in the accounting process; however, the accounting rules are consistent with those used to quantify the effect of CDRs, explained below.

Concerning in-boundary carbon removals, the methodology enshrined in the CRCF (European Parliament and Council, 2024b) is here adapted to the Cities Mission context. The net removal should be computed following two steps:

- **Quantification of removals**. Quantification of the amount of removals that a GGR has generated in the accounting year. As removals risk being released back into the atmosphere due to natural or anthropogenic causes, those responsible for the activity should take all relevant preventive measures to mitigate those risks (e.g., maintenance activities) and duly and regularly monitor that GHGs continue to be stored over the monitoring period laid down for the relevant removal activity. If reversals are detected, these should be reflected in this step.
- **Quantification and subtraction of associated GHG emissions**. Any increase in direct and indirect GHG emissions directly attributable to the implementation of the activity in the accounting year is quantified and subtracted. Relevant GHG emissions that should be taken into consideration include direct emissions, such as those resulting from the use of fertilisers, chemicals, fuel or energy, other material inputs and transportation, or indirect emissions, such as those resulting from land use change. For a fully climate-responsible management of GGRs, all 7 GHGs, all 5 sectors, and all 3 scopes included in the Cities Mission's definition of climate neutrality should be considered in the decision-making process, to support removal activities with minimal leakages on global emissions. However, for consistency in accounting, the emissions of gases and from the sectors and scopes included in the corrected target boundary should be included in this step.

The outcome of the net removal calculation should be expressed in tonnes of carbon dioxide equivalent and should be included in the computation of $GHG_{net}$ as negative and positive emissions, respectively (see **Section 6.2**). However, where the increase in GHG emissions outweighs the carbon removals, the city is advised to discard the activity and investigate other options. This may be the case of an afforestation or a peatland re-wetting activity where the carbon removal does not outweigh the emissions from the machinery used to carry out the activity or the indirect land use change emissions. When a net-source activity is maintained within the portfolio of actions

(for instance because it triggers a series of changes that together yield a net benefit for mitigation, or because it addresses other urgent environmental, social or economic demands) a clear explanation for this decision should be provided and examined within the action plan.

Further, it is noted that a reduction in GHG emissions resulting from the implementation of the removal activity should not be taken into account to quantify the net removal benefit, but should be considered as an emissions reduction, achieved as a co-benefit of carbon removals towards the climate neutrality target.

Both removals and emissions should be representative of the city contribution in the accounting year (see also **Box 25**). Cities are encouraged to conduct an annual assessment of carbon sink contributions, considering factors such as the time required for natural sinks to fully develop their sequestration potential and their yearly impacts (**Box 24**).

**Box 24**. Asynchronous emissions accounting across sectors

Land sector inventories are typically updated after several years, hence they may not occur with the same frequency as inventories for other sectors. The main reasons for this potential asynchrony are i) data availability (scarcity of data or complexity in data collection make it unlikely to guarantee annual or biannual availability), and ii) disturbances (whose effects are better smoothed out when reporting occurs as an annual average over a period of several years). The recommended practice for the land sector is to convert total GHG fluxes from multiyear inventories into an annual average (i.e., annualisation).

In principle, when a removal occurs in geographic areas partially inside and partially outside (yet adjacent to) the target boundary, the in-bound share can be directly accounted for under $GHG^{-}$ (see **Section 6.2**), while the share that occurs outside the boundary would have to be turned into carbon credits and retired ($CC_{retired}$). This approach assists in controlling for potential double counting across neighbouring administrations. However, it is recognised that in certain cases, requiring cities to undergo a crediting process for activities occurring in close proximity to the city boundaries may be impractical. To address this, a degree of tolerance can be applied, provided that robust mechanisms are in place to prevent double counting and ensure the accuracy of claims. This approach would allow for a more pragmatic and flexible implementation, while still maintaining the integrity of the system and preventing potential illegitimate claims and fraud.

For removals that transcend the target boundary into neighbouring areas, long-term planning and fairness considerations might also apply (see **Box 20**). On the other hand, large-scale natural carbon sinks that transcend the city boundary are expected to deliver significant co-benefits that may become even visible as GHG reduction. This is the case of e.g., vast afforestation programmes and the urban cooling effect they may generate, since lower temperatures, especially in dense cityscapes and cooling-dominated climates, could result in significant energy conservation and heat island mitigation.

Separate tracking and reporting should also apply to areas inside the GHG accounting boundary where local policies do not apply, such as national parks or areas managed by carbon project developers. Finally, where a portion of city land is designated as unmanaged and excluded from the inventory, justification shall be provided on the methods used to delineate the unmanaged land and geospatial boundaries shall be provided in documentation (WRI et al., 2022).

**Box 25**. Natural and anthropogenic disturbances

The expression “natural disturbances” is used to indicate discrete events such as fires, windstorms, hurricanes, landslides, and tsunamis, or more continuous perturbations such as a pest outbreak or

prolonged drought. These phenomena can cause large fluctuations in GHG inventories and are beyond the control of, and not materially influenced by, the city. In line with the CRCF framework, operators shall aim to enhance the resilience of the activity area by putting in place practices that mitigate the risks of reversals. However, within the Cities Mission's framework, cities may exclude from their accounts the effect of natural disturbances, on the grounds that:

— Quantifying emissions and removals associated with natural disturbances can be a highly complex and data-intensive process. It may come with high additional accounting and reporting burden to weigh the potential for large emissions impacts from natural disturbances against the costs of establishing and implementing a mechanism to address those emissions.

— The Cities Mission focusses on taking responsibility for deliberate anthropogenic activities, rather than for uncontrollable natural events. Nonetheless, when significant distortions in the real GHG emissions budget are currently experienced or foreseeable in the future as a result of natural disturbances, cities are expected to take precautions (and discuss them in the action plan).

It is to be noted that, even if natural disturbances are factored out, the emissions stemming from subsequent anthropogenic activities that generate emissions, such as prescribed burning, harvesting and salvage logging, or subsequent changes in land use, should be factored in (European Parliament and Council, 2018; Levin et al., 2014).

On the other hand, cities may decide to use a natural disturbance accounting mechanism for individual categories, activities or sectors, as described in (Levin et al., 2014) and other relevant documents cited therein.

Accounting for negative emissions is particularly relevant for the AFOLU sector. When the whole AFOLU sector is incorporated in the corrected target boundary, GHG emissions from agriculture and fisheries, on the one hand, and GHG emissions and removals from e.g., forest land, cropland, grassland and wetlands, on the other, should be accounted for. This is discussed in **Section 7.1**.

For forests and urban trees, detailed guidance for cities has been made available over time and is thus discussed in the following (**Section 7.1.1**). For other CDRs, cities are invited to consult relevant methodologies designed by the IPCC, enshrined in the Renewable Energy Directive (European Parliament and Council, 2023a), or in other reputable sources. An excursus is provided for wetlands restoration in **Section 7.1.2**, by means of example.

Nonetheless, the general accounting approach described above can be always applied. It is noted that Mission Cities should always and clearly state in their CNAP the accounting method in place for any item of their emissions inventories and the rationale for choosing specific factors to translate activity (or other) data into GHG emissions or removals.

## 7.1 The land sector

Land Use, Land Use Change, and Forestry (LULUCF) is the most complex sector in terms of modelling of emissions and removals within the UNFCCC reporting framework. In order to obtain accurate accounts of emissions and removals in accordance with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories and their 2019 refinement, cities should estimate the mitigation potential of compensation strategies, while measuring the mitigation effect that is already in place and legacy effects (**Box 29**). Further, the potential dual role of e.g., forests, trees, and soils as GHG sources (emissions exceed removals) and sinks (removals exceed emissions), along with their variability over time in response to both human and natural processes, poses

unique monitoring challenges for cities (WRI et al., 2022). In addition, the contribution of land sinks to urban net-zero targets is expected to be limited and the like-for-like principle would encourage to account for differences in permanence between the warming effect of fossil $CO_2$ emissions and the cooling effect of land-based $CO_2$ removal (Brunner et al., 2024).

This complexity should not discourage cities from incorporating the land sector in their emission inventories and in their residual emissions strategy, as the land sector is a great source of benefits and co-benefits in climate action and in guaranteeing healthy urban futures. The land sector has mitigation potential through reducing emissions and enhancing carbon sinks. The sector further contributes to bio-materials (that can substitute fossil- or carbon-intensive materials) and to the productivity, regeneration capacity and vitality of the land via sustainable and innovative management practices (e.g., agro-ecology, agro-forestry) thereby promoting economic and social development beyond climate mitigation, climate adaptation, and biodiversity protection.

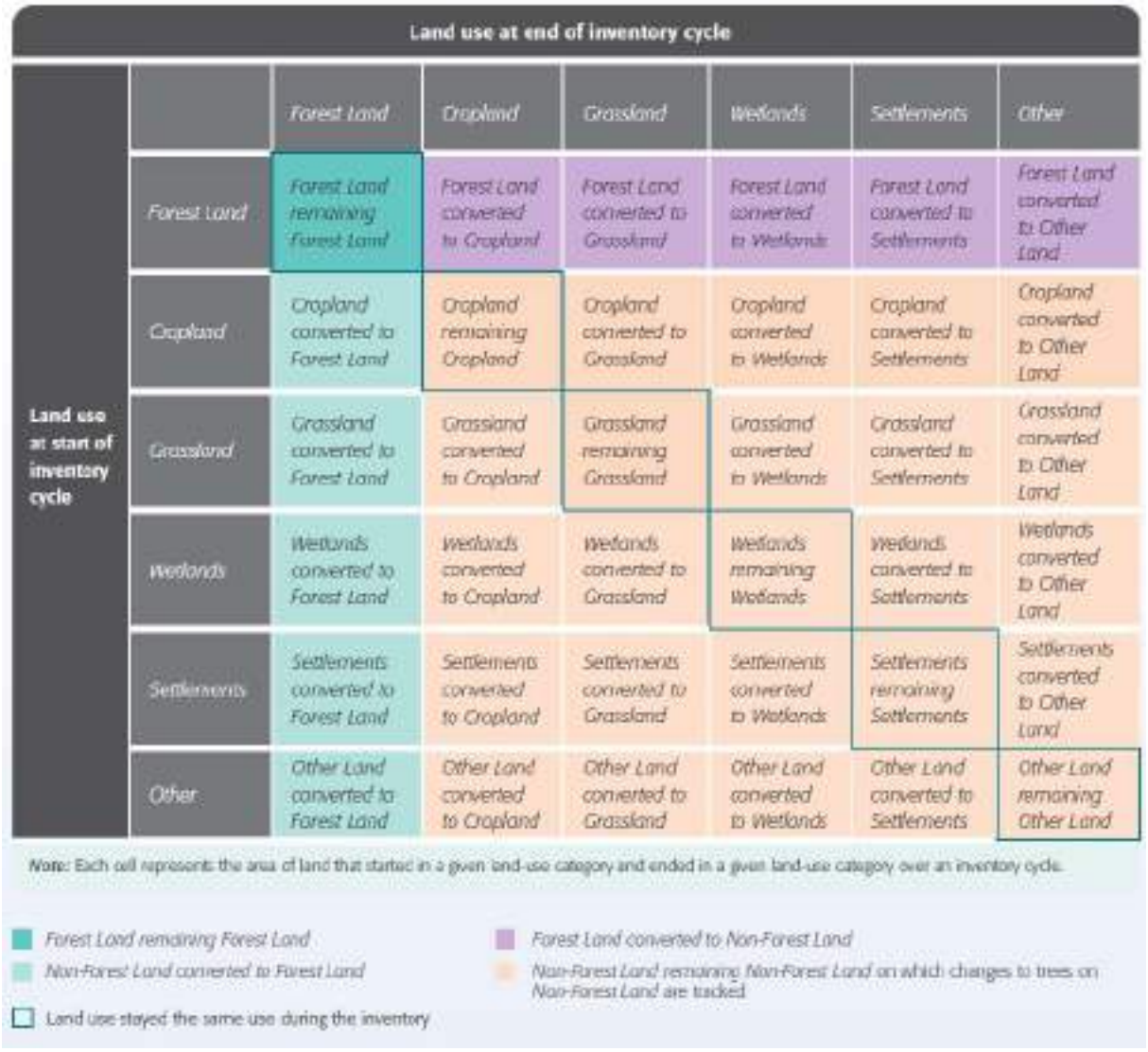
Cities can choose between two land sector accounting approaches: land-based accounting or activity-based accounting. The difference is that land-based accounting associates positive and negative emissions with land use categories (e.g., forestland, cropland), while activity-based accounting attributes emissions to the activities that pertain to the land sector (e.g., soil carbon management, wetland drainage). The choice depends on capacities, data availability, priorities, and objectives[11]. More information and guidance can be found in (Levin et al., 2014). In the following, this guidance refers to land-based accounting as this is the most common approach, including in dedicated regulation and certification frameworks (European Parliament and Council, 2018, 2024b).

In the IPCC reporting framework, land is classified into six land use categories: forest land, cropland, grassland, wetland, settlement, and other land (IPCC, 2019a), where land use is not equivalent to land cover (**Box 26**). The six IPCC land use categories (explained in **Box 45** in **Annex 1**) may be disaggregated into additional subcategories to improve calculations or to increase detail in reporting (WRI et al., 2022). Urban areas general fall within the settlement category, which encompasses all developed land such as residential, commercial, production, and transportation infrastructures. It includes also lawns, gardens, parks, and land along streets, as long as they are functionally associated with settlements and not classified under another land-use category.

On top of land use, its change shall also be estimated. A land use change matrix could be used to identify the activity data needed for accounting calculations (see **Table 8** from (WRI et al., 2022)). At least two land use maps (or equivalent) representing two different points in time are needed to establish the land use change matrix (i.e., data from one point in time can provide information only on land use and/or carbon stocks). A separate land use change matrix should be created for each inventory cycle. It is noted that, 20 years after the land use change occurred and provided that no other land use change affects the same area, the “land converted to another type of land” (i.e., the categories sitting outside the diagonal of the matrix) should change category into some “land remaining the same type of land” (i.e., categories along the diagonal). In some instances, and if duly justified based on the IPCC Guidelines, the time can be increased to 30 years (see Articles 5 and 6 in (European Parliament and Council, 2018, 2023b)).

[11] It should be noted that the principles of exhaustiveness and exclusiveness discussed further down in this section may be more complicated to handle when activity-based reporting is selected.

**Table 8**. Land use change matrix




*Source: (WRI et al., 2022).*

**Box 26**. Land use is not the same as land cover

Land cover and land use should not be conflated. Although land cover is often easier to map than land use as it is remotely observable, it may not be immediately useful for inventories as the physical and biological attributes of land (such as whether there are trees) are not always consistent with the use of the land. Inferring land use from land cover could result in attributing GHG emissions and removals to the wrong land use category (WRI et al., 2022) or could erroneously suggest land use changes where temporary land cover changes occur. Nonetheless, it is acknowledged that using land cover as a proxy for land use may be a reasonable simplification for city inventories. In this case, the implications in terms of uncertainty should be discussed and consistency should be ensured as much as possible across different inventories (see **Section 7.3**).

The level of aggregation or disaggregation that a city provides with respect to its land use categories and activities needs to be aligned with the climate neutrality target (as set out in the CCC for Mission Cities). It is noted that this decision will influence the city's understanding of what mitigation actions and policies may be effective to deliver climate neutrality. For this reason, while alignment with the IPCC, Global Protocol for Community-Scale Greenhouse Gas Emission Inventories

(GPC), national or subnational land use categories is recommended for consistency, comparability, and potential aggregation, cities may decide to use a different system or definitions more respondent to local specificities (see also **Box 27**). Cities may also wish to include land-ownership types, that distinguish e.g., publicly from privately owned land, as this may ease the distribution and management of responsibilities in climate action. In all these cases, a compelling rationale should support the use of different categories. Cities should determine the appropriate level of aggregation or disaggregation for their inventory early in the inventory compilation process, on account of their advantages and disadvantages (see Table 8, Case Study 1 and Case Study 2 in (WRI et al., 2022)).

**Box 27**. Interaction between city-level GHG accounting and EU/national frameworks

Local accounting approaches operate within a broader legal and compliance architecture defined at EU and Member State level. Because EU climate legislation establishes binding obligations only for Member States (not municipalities), it is important that local accounting relates to national reporting and compliance systems. Wherever possible and adequate, cities could align methodologies with national inventory approaches to facilitate consistency and aggregation.

Under the European Climate Law, the EU has established a binding framework for achieving climate neutrality by 2050 and intermediate targets for 2030 and beyond. Within this architecture, compliance obligations apply to Member States and implementation is operationalised through instruments such as the Effort Sharing Regulation (ESR), the EU ETS, and the LULUCF Regulation (see also **Section 9**). National inventories follow standardised methodologies and sectoral boundaries defined internationally. City inventories, by contrast, are voluntary and may use different accounting scopes, sector definitions, and baselines.

Net removals from LULUCF are counted toward Member State compliance with EU climate targets, including towards national ESR targets. Cities reporting removals occurring within their territory or selling carbon credits generated from local removals can create safeguards for correct accounting at national level by reporting them transparently. Doing so minimises the risk of double counting, clarifies ownership of mitigation outcomes, and ensures that local climate leadership strengthens the integrity of the wider climate policy framework.

Regardless of the specific land use categorisation, cities should ensure (WRI et al., 2022):

— The **exhaustive** assignment of land uses in agreement with the target boundary: this means that no land use that forms part of the city's target should be omitted (no undercounting).

— The **exclusive** assignment of land uses: this means that no land is assigned to two categories (no double counting). Where land use could fall into multiple categories (e.g., an agroforestry system could be cropland or forest land, cattle grazing and forest management activities could occur in the same area, or forested wetlands could be classified as forest land rather than wetlands), one land use shall be assigned. The GPC prescribes the following hierarchy: Settlements > Cropland > Forest Land > Grassland > Wetlands > Other Land (WRI et al., 2022).

Compliance with the conditions of exhaustiveness and exclusiveness should be demonstrated in the action plan.

Once the land categorisation is completed, each category should be assigned its $GHG^{+}$ and $GHG^{-}$ contribution to net emissions. This applies also in case of unchanged land use (**Box 28**) and could account for legacy effects (**Box 29**).

**Box 28**. Unchanged land use is not unchanged carbon stock (adapted from (WRI et al., 2022))

Land staying in the same land use category throughout an inventory cycle may observe changes when it comes to accounting emissions. For instance:

— Substantial removals can occur in a city's Forest Land remaining Forest Land as, for instance, old-growth forests that remain undisturbed over the inventory may store and remove substantially more carbon.
— Emissions can occur from a change of condition in Forest Land remaining Forest Land, such as disturbance or management.
— Changes to tree canopy can result in emissions from loss of tree canopy and removals due to or resulting from maintaining and/or increasing the Non-Forest Land tree canopy area over time.

**Box 29.** Legacy effects

Emissions and removals associated with the land sector depend on a number of natural (i.e., non-anthropogenic) circumstances. Beyond natural disturbances (discussed in **Box 25**), dynamic age-related forest characteristics and earlier land use management practices may produce "legacy effects" that continue to influence emissions and removals after the original activities have ceased.

Past and present management practices may differ substantially between Member States and even at sub-national level. Reliable geographically explicit data and scientific evidence would be required to quantify their impact on a city-by-city basis. While this exercise is encouraged, but not required, in the context of the Cities Mission, cities should acknowledge any legacy effect that causes significant distortions in their local emissions and removals and describe policy measures currently implemented or to be implemented by the net-zero target year to minimise any negative impacts.

Reporting for the land sector should include information on the criteria used to distinguish anthropogenic from non-anthropogenic carbon fluxes, along with a justification on the selected accounting methodology. Additional information on how to deal with non-anthropogenic effects can be found in (Levin et al., 2014).

According to the IPCC guidelines (IPCC, 2006, 2019a), there are two fundamentally different yet equally valid approaches to estimate $CO_2$ (positive and negative) emissions from land. These may be adapted to other GHGs:

— the stock-difference method, which estimates the difference in carbon stocks (i.e., total amount of carbon in a given reservoir) at different points in time; and

— the gain-loss method, which estimates the net balance of additions to and removals from a carbon reservoir.

The two methods should give essentially the same result in terms of emissions, but differ in terms of effort, uncertainty, and agreement with the guiding principles outlined in **Section 6**. The stock-difference method was found to produce considerably smaller estimates of uncertainty (McRoberts et al., 2018); however, results are most statistically robust where there are relatively large increases or decreases in estimated biomass, or where there are statistically rigorous inventories available over multiple years (Penman et al., 2003). Further, this method does not allow for the estimation of emissions and removals separately (WRI et al., 2022), thus violating the Transparency Principle (**Section 6.2**). Conversely, the gain-loss method follows the typical approach used in GHG inventories for other sectors: emissions are estimated as the product of activity data and emission factors (i.e., the amount of carbon emitted by each carbon reservoir per unit of land area), while

removals are estimated as the product of activity data and carbon gain factors[12] (i.e., the amount of carbon accumulated per unit area of land use or land use change per year). The gain-loss method does not estimate the actual biomass stocks, which has advantages in certain situations. For example, it is nearly impossible to apply the stock-difference method to soil carbon in peatland, but relatively straightforward to implement the gain-loss approach (Bird et al., 2010). For all these reasons, and considering that cities typically lack a consistent track record of inventories in the AFOLU sector (Penman et al., 2016), this guidance focusses on the gain-loss method. However, cities may consult other detailed guidance on land sector accounting, such as the 2006/2019 IPCC Guidelines (IPCC, 2006, 2019a), the 2003 IPCC Good Practice Guidance for Land Use, Land use Change and Forestry (IPCC, 2003), the 2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol (IPCC, 2014a), or the 2014 Mitigation Goal Standard by the World Resources Institute (Levin et al., 2014).

### 7.1.1 Forests and trees

Cities that include the land sector in their corrected target boundary, should account for the GHG fluxes associated with forest land and trees on non-forest land and those stemming from forest-related land use transitions (i.e., deforestation and afforestation or reforestation; see also **Box 30**). The World Resources Institute (WRI), ICLEI–Local Governments for Sustainability, and C40 Cities Climate Leadership Group published in 2022 a guidance for estimating GHG emissions and $CO_2$ removals associated specifically with forests and trees within the boundaries of cities, towns, counties, or other subnational jurisdictions (WRI et al., 2022). As in the GPC and U.S. Community Protocol, the guidance is informed by, and broadly consistent with, the 2019 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019a).

**Box 30.** Cross-sectoral impacts of forests and trees (adapted from (WRI et al., 2022))

> Forests and trees intersect other sectors in a GHG inventory, notably the stationary energy sector (e.g., in relation to the burning of biomass or agricultural residue) and the waste sector (e.g., biomass that goes to landfill). Biomass extracted from forest land is also used to produce harvested wood products that store carbon for various durations, from short periods (e.g., paper) to very long periods (e.g., furniture or in building construction). The substitution effects of using such products can also impact other sectors; for example, using wood for buildings compared to energy-intensive materials such as cement or steel (IPPU sector).

The guidance proposes a gain-loss method for estimating emissions and removals separately (hence in accordance with the Transparency Principle) by combining activity data with emission and carbon gain factors. The following land use categories are concerned:

[12] The term carbon gain factor is used to avoid confusion with the term removal factor, which may be associated with technological or biological carbon dioxide removal processes that permanently remove $CO_2$ from the atmosphere. The carbon gain factor is formally analogous to the emission factor.

— Forest land (FL), covering GHG emissions that result from FL converted to a different land category (deforestation) and emissions occurring on FL remaining FL resulting from disturbances, such as fires and timber harvesting. It covers removals associated with other land categories converted to FL (afforestation or reforestation) and removals occurring on undisturbed FL remaining FL[13].

— Non-forest land (NFL), i.e., cropland, grassland, settlement, wetland, and other land. It covers GHG emissions and removals associated with trees on NFL. For cities, this typically includes i) urban land with tree cover (settlements), ii) agroforestry systems (cropland), and sparse tree cover (grassland). This broad category includes anything from small yards to urban parks. The guidance focusses on woody perennial vegetation (i.e., not herbaceous vegetation) on the grounds that the carbon stored in the woody components of trees makes up the largest compartment of standing biomass stocks and annual biomass increment in NFL (see **Box 31**).

It should be noted that while GHG emissions associated with soil in FL are included, GHG fluxes associated with soils in NFL are not covered. **Table 9** illustrates in greater detail the GHG sources/sinks and scopes addressed by the guidance.

**Table 9**. GPC Supplemental Guidance for Forests and Trees: GHG sources/sinks and scopes

| **Domain** | | **Addressed** | **Unaddressed** |
|---|---|---|---|
| **GHG source/sink** | Forest Land | Emissions (biomass and soil) and removals (biomass only) by Forest Land, including land use changes and forest disturbances. | Changes in carbon stored in harvested wood products or substitution effects for harvested wood products, changes in deadwood or litter pools in Forest Land. |
| | Non-Forest Land | Emissions from and removals by trees on Non-Forest Land (biomass only). | Non-tree aspects of Non-Forest Land (e.g., soil carbon changes on agricultural lands or wetlands). |
| | Soil | Emissions from soil during land use changes involving Forest Land (deforestation). | Carbon sequestered by Forest Land soils, and all aspects of managed soils on Non-Forest Land (e.g., Cropland, Grassland, Wetlands). |
| | Biomass or residue burning | $CO_2$ and non-$CO_2$ emissions from forest fires. | Biomass burning for energy (reported in the stationary energy sector) |
| | Biomass in landfill | N/A | Any aspect (reported in the waste sector) |
| **Scopes** | | Scope 1 emissions and removals (territorial GHG fluxes). | Scope 3 emissions (e.g., GHG emissions associated with displacement of land development to nearby cities due to maintenance or growth of urban tree cover in the inventoried city, GHG consequences of land use change caused by consumption of products within the community). |

*Source: JRC analysis (adapted from (WRI et al., 2022)).*

[13] The IPCC reports land-use conversions under the final land-use category. Accordingly, Forest Land is the sum of Forest Land remaining Forest Land and land converted to Forest Land, while deforestation is reported under the land-use category to which the forest is converted. Here, all forest-related categories are brought under the same umbrella to align with the WRI, ICLEI, & C40's "Global Protocol for Community-Scale Greenhouse Gas Inventories: Supplemental Guidance for Forests and Trees" discussed in this Section.

**Box 31.** Why the focus is on forests and trees?

Carbon removal, or carbon sequestration, is more prominent in trees and forests compared to smaller plants mostly due to differences in the balance between photosynthesis and respiration.

Both trees and smaller plants undergo photosynthesis to capture carbon dioxide from the atmosphere and convert it into organic compounds, primarily carbohydrates. However, they also undergo respiration, where they consume those carbohydrates to produce energy for metabolism. During respiration, a portion of the carbon stored in carbohydrates is released back into the atmosphere as carbon dioxide.

The difference between the rates of photosynthesis and respiration arbitrates the net carbon sequestration. Trees, especially those in forests, tend to have a higher net carbon sequestration rate compared to smaller plants due to several factors:

— **Slower metabolism**: Trees generally have slower metabolic rates compared to smaller plants. This means that they respire less per unit of stored carbon, resulting in more efficient carbon storage.

— **Size and lifespan**: Trees are larger and have longer lifespans than most other plants. This means they can store more carbon over time as they grow and mature.

— **Greater biomass**: Trees have a significant amount of woody biomass, which allows them to store carbon for longer periods. This carbon can remain stored in the form of wood for decades or even centuries.

— **Root systems**: Trees often have extensive root systems that can store carbon in the soil, contributing to carbon sequestration beyond just aboveground biomass.

— **Density**: Forests, composed mostly of trees, are generally denser than other plant ecosystems. This density contributes to more effective carbon storage per unit area.

— **Regeneration**: When trees die, they often contribute to the formation of new soil, which can sequester carbon over time as well.

In summary, while all plants undergo both photosynthesis and respiration, forests and trees are more effective at long-term carbon removal due to their larger size, slower metabolism, longevity, and the ability to store carbon in various forms, including woody tissues and soils.

As forests and trees both emit $CO_2$ into and remove $CO_2$ from the atmosphere, and as they can also emit other GHGs such as methane ($CH_4$) and nitrous oxide ($N_2O$), the guidance instructs on how to determine both positive and negative GHG contributions. The key steps for emissions accounting are:

— Identify the land use and land use change categories to be included in the inventory.

— Select appropriate data sources.

— Calculate and assign activity data, emission factors, and carbon gain factors.

— Calculate emissions and removals associated with forests and trees.

While the calculations to estimate forest- and tree-related GHG fluxes are relatively straightforward, the process of identifying data sources for activity data, emission factors, and carbon gain factors may be the most complicated part of the inventory and is frequently iterative (see **Sections 7.1.1.1 and 7.1.1.2**). Methods to reduce uncertainty and ensure exhaustive and exclusive coverage are discussed in **Section 7.3**. It is recommended to consult directly (WRI et al., 2022) for more detailed guidance.

#### 7.1.1.1 Data sourcing, calculation and assignment

**Table 10** summarises the main activity data needed to complete the forest and trees GHG inventory. Data sources may vary considerably across different cities. Therefore, each city should carefully select the sources that best balance different objectives (e.g., accuracy, continuity of provision and frequency of updating, level of detail, geographic coverage). No single data source may meet all the desirable criteria and multiple data sources could be - appropriately - combined. The data sources and rationale for selection should be both documented in the action plan. Activity data needed for calculating GHG fluxes associated with FL include forest-related land use changes (deforestation and afforestation or reforestation), as well as information about any forest disturbances (see **Box 25** on how disturbances can enter the accounting process). For NFL, the foundation for calculating the GHG fluxes typically revolves around estimated measurements of the area of tree-canopy cover and canopy-cover change during the inventory cycle, based on censuses of individual trees (possibly disaggregated into species or families and possibly containing information on tree health and mortality – see **Box 32**) or on canopy cover/crown area mapping or sampling. Regardless of the method used, the outcome of this step is the quantification of the area of tree cover or of the number of trees on NFL that are lost, gained, or maintained. Multi-year surveys would be needed for both FL and NFL, to calculate changes in canopy. Extracted from (WRI et al., 2022), **Figure 6** provides a decision tree for selecting sources of activity data for both land use categories.

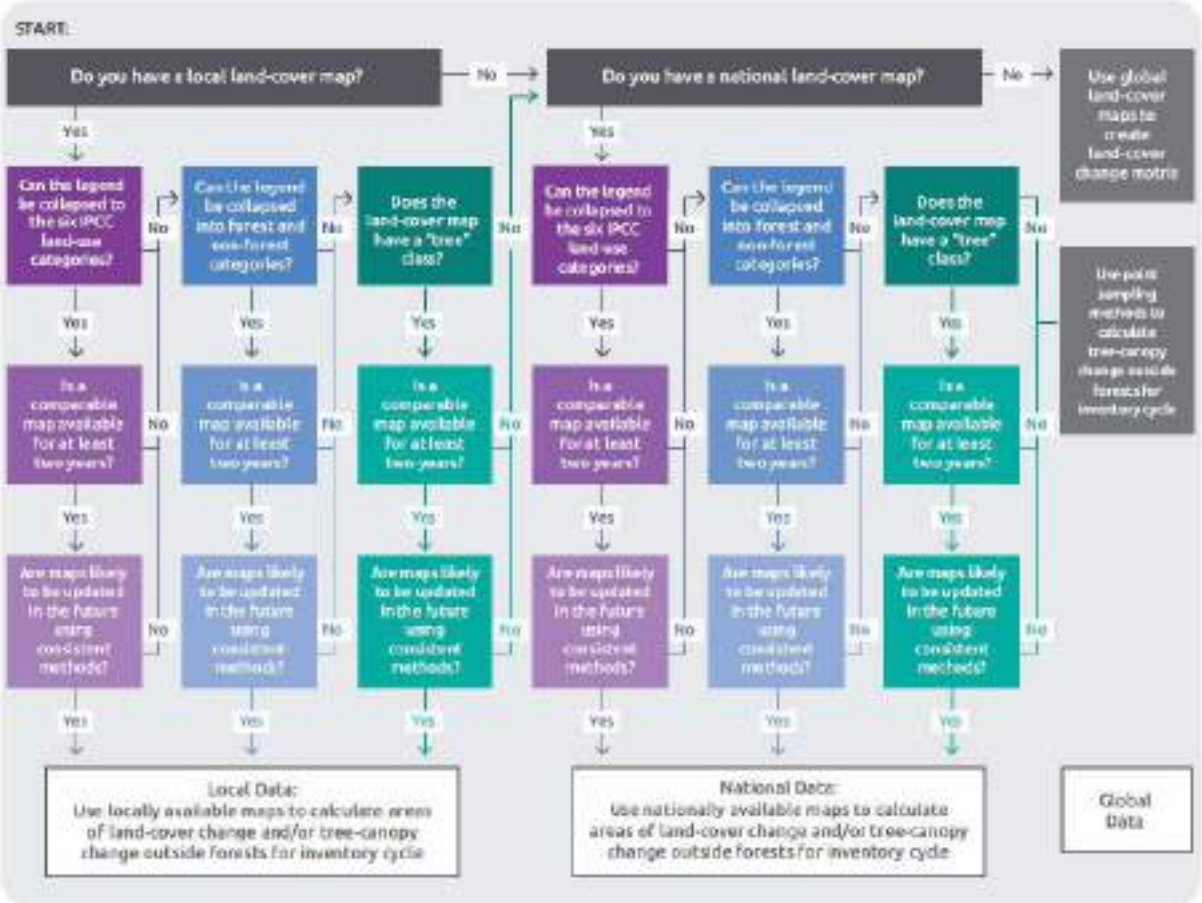
**Table 10.** Summary of data types needed for compiling a GHG inventory for forests and trees. Where the city decides to exclude disturbances all relevant data points can be disregarded. It is noted that in the IPCC framework, i) harvest is not considered as a disturbance, ii) emissions from living biomass and normal forest management is usually estimated from the wood harvest quantities (rather than from the area of forest harvested) modelled into dry matter according to e.g., the forest types, iii) similarly, for fires, the activity data is not the area burned, rather the fuel (i.e., the amount of biomass burned).

| | Row | Data Category | Sub-category | Type of Data Needed (Units) |
|---|---|---|---|---|
| *Forest Land* | 1 | Activity data | Land-cover change / land-use change | Land-cover or land-use maps for multiple years (to derive land-use change matrix) (ha) |
| | 2 | Activity data | Forest disturbances | Area (and location and intensity) of *Forest Land* burned (ha) |
| | 3 | Activity data | Forest disturbances | Area (and location and intensity) of *Forest Land* harvested (ha) |
| | 4 | Activity data | Forest disturbances | Area (and location and intensity) of other disturbances (pest, wind, etc.) on *Forest Land* (ha) |
| | 5 | Activity data | Forest disturbances | Annual timber harvest, fuelwood statistics ($m^3$ for timber or fuelwood; t for fuelwood) |
| | 6 | Activity data | Forest subcategories | Area (and location) of different forest types, ownership classes, etc. (ha) |
| | 7 | Emission factors | Forest emission factors | Forest carbon density in different forest types and pools (aboveground biomass, belowground biomass, deadwood, litter, soil organic carbon) (t C/ha) |
| | 8 | Carbon gain factors | Forest carbon gain factors | Mean annual increment or biomass carbon accumulation rate in different forest types and/or age classes (t C/ha/yr) |
| *Non-Forest Land* | 9 | Activity data | Trees on *Non-Forest Land* | Area of tree canopy or tree census for multiple years (ha of tree canopy or # of trees) |
| | 10 | Activity data | Trees on *Non-Forest Land* subcategories | Area (and location) of different *Non-Forest Land* subcategories (ha) |
| | 11 | Emission factors | Trees on *Non-Forest Land* emission factors | Carbon density in trees on *Non-Forest Land* (t C/ha of tree canopy or per tree) |
| | 12 | Carbon gain factors | Trees on *Non-Forest Land* carbon gain factors | Biomass carbon accumulation per area of canopy cover or per tree by trees on *Non-Forest Land* (t C/ha/yr or t C/tree/yr) |

*Notes:* Not all data types are needed for all communities. For example, not all communities have burned forest.
C = carbon; ha = hectares; t = metric tonnes; yr = year.

*Source: (WRI et al., 2022).*

**Figure 6**. Decision tree for selecting sources of activity data.




*Source: (WRI et al., 2022).*

Emission factors are highly dependent on the presence, nature, and severity of changes, whereas carbon gain factors are dictated by the age, type, and climate conditions of forest and tree growing (WRI et al., 2022).

For both factors, local - possibly georeferenced - data is always to be preferred over more generic estimates (such as IPCC defaults from National GHG Inventory Guidelines). Beyond greater accuracy and customisation to local specificities, a co-benefit of locally produced data is the mobilisation of local stakeholders, which may be critical to interpret disturbances or temporary land cover changes (historical knowledge) and to raise awareness on the need for maintaining and expanding the ability of forests and trees to capture and store carbon. However, when cities lack access to site-specific data, they should investigate the use of regional/national data (e.g., National Communications to UNFCCC, Forest Reference Emission-Level reports, National Forest Inventories) or IPCC defaults (Institute for European Environmental Policy, 2015). This is a very frequent case when it comes to trees on NFL, for which measurements of carbon densities or annual carbon increments are extremely rare across cities in Europe and beyond. If tree censuses are available, data on e.g., tree height, dieback, crown light exposure, health status can be converted into estimates of emission and carbon gain factors, otherwise if the area of tree canopy is available, urban tree carbon gain factors for settlement land use could be adopted as these exhibit closer stocking density as compared to factors applied to forest land. As a last resort, the IPCC defaults may be used (2.8 t C/ha tree canopy/year for nonboreal regions, 2.1 t C/ha tree canopy/year for boreal regions, for trees younger

than 20 years old) (IPCC, 2019a). For emission factors, where no carbon density data is available for trees on NFL, a default of 80% of forest carbon density can be used (IPCC, 2019b).

Difficulties in estimation are also common for FL carbon gain factors, as "last-minute" monitoring campaigns would not serve the scope. A low-uncertainty definition of carbon gain factors requires repeated measurements of forest carbon over multiple years, usually from forest inventories, which are resource-intensive and require large samples. On the other hand, emission factors are often derived from field measurements of tree carbon density, or sometimes from remote-sensing approaches with field validation.

**Box 32.** A healthy and growing tree is a better service provider

As highlighted in the recent amendment to the LULUCF Regulation (European Parliament and Council, 2023b) – presented in **Section 9** - forests and healthy soils are extremely important for carbon sequestration and storage, biodiversity, purification of air and water, and provision of sustainably sourced long-lived wood products. They can deliver a number of important regulating services in the urban ecosystem (including evaporative cooling), yet the health and age condition of trees and forests affects their service-providing capacity to a high degree (Kiss et al., 2015).

This entails that a robust and longstanding residual emissions strategy looks at the whole lifecycle of forest and trees, at the physiology and stress tolerance of the species, and at side effects, with a critical perspective on the emissions that may be generated in the process. Even forests, when unhealthy, can act as a carbon source. During their lifetime, trees draw carbon out for as long as they grow. If the case occurs and the forest is deprived of more carbon through death and decomposition processes than it can bind through photosynthesis, it becomes a carbon source. Climate change exacerbates this risk. Global warming increases the vitality of many forest pests and pathogens, wind damages are enhanced because of a shorter period of frozen soil to provide a firm anchorage against storms, and wind-thrown trees serve as starting points for bark beetle outbreaks (Pukkala, 2018). The nature and function of forests is highly variable across the EU, with certain types of forests being more vulnerable to climate change (drought, temperature-induced forest dieback or changes in aridity). Further, beyond abiotic factors (e.g., nutrient availability, soil characteristics and climate), forest age is a dominant factor to the net ecosystem productivity (i.e., net carbon exchange between the ecosystem and the atmosphere) (Besnard et al., 2018).

Species-rich and unevenly sized forests can improve the carbon storage potential in biomass and topsoil across their development. Increasing evidence highlights that mixed-species forests can provide multiple ecosystem services at a higher level than their monospecific counterparts. Forests with a high species diversity are more productive (i.e., enhanced wood growth) and more stable in the face of stress than those that are uniformly composed. Studies show that the mean overyielding (higher productivity in mixtures than in monocultures) can reach 25%–30% in two- and three-species mixtures and may exceed 50% in five-species stands (Erskine et al., 2006; Schnabel et al., 2019). Further, overyielding and asynchronous responses of species to environmental variability result in higher temporal stability of productivity, with overyielding reaching its peak under stressful environmental conditions (e.g., drought) (Schnabel et al., 2019). These positive diversity–productivity and diversity–stability relationships result in considerably higher carbon stocks. On the other hand, tree-size heterogeneity can regulate the temporal dimension of forest ageing to enhance the carbon storage potential (Hernández-Alonso et al., 2023). Depending on the local environment and the intrinsic tree ontogeny (i.e., development process), mature forests may be unable to store carbon and would need to grow structurally diverse.

Increasing the forests and urban trees diversity can also promote better responsiveness to local climate and social health:

— Introducing drought-resistant species may reduce tree mortality against the escalating frequency and magnitude of extreme heat events across all Europe (Feyen et al., 2020), while selecting species that have higher albedo would reduce local heat.

— Introducing species that are low-emitters of volatile organic compounds (BVOCs) would positively impact local warming and air quality, as BVOCs are precursors of tropospheric ozone and atmospheric aerosols, promoting the formation of secondary pollutants such as peroxyacetyl nitrate (PANs), secondary organic aerosols (SOA), particulate matter (PM), aldehydes and ketones (Laothawornkitkul et al., 2009).

— Selecting urban trees species that have little to no impact on asthma, wheeze, rhinitis, and allergic sensitisation could ameliorate citizens' health (Lovasi et al., 2013).

Overall, afforestation, reforestation, and other tree planting processes should be developed in a climate sensitive manner that maximises the growth potential and overall health of selected species. This would increase the chances that trees keep acting as carbon sinks even under changing climatic conditions and disturbances, while multiplying benefits and co-benefits.

On the other hand, trees diversification and health preservation may require more complex maintenance procedures. As maintenance activities typically generate emissions, it is critical that the negative impact is at least balanced by the increment in stock density. Furthermore, diversification for maximum carbon sequestration should not distort the native composition. When using exotic tree species, concerns arise around trade-offs with other ecosystem services and the permanence of the carbon storage given the (possibly untested) vulnerability of these species to e.g., local weather fluctuations, fire and pathogens. Nature-based solutions that respect biodiversity protection, restoration and sustainable management of native ecosystems typically involve fewer trade-offs and are more resilient (Fankhauser et al., 2022).

All these considerations should enter the calculation of emission and carbon gain factors.

**Cities in the spotlight: Barcelona (Spain) and Sofia (Bulgaria)**

Barcelona's carbon sink governance stands out in that it prioritises the health and resilience of urban trees to maximise their social, economic, and environmental functions (Barcelona, 2024). The city focusses on creating a **diverse and adaptable tree stock**, with no single species dominating the urban landscape, to ensure a robust and thriving ecosystem. By promoting **healthy trees**, the city aims to enhance their role in mitigating climate change, while also fostering social interaction and community engagement with urban nature. The plan recognises the importance of trees in providing social and economic services, such as improving air quality, reducing urban heat islands, and supporting public health and wellbeing. By engaging citizens and promoting a **culture of appreciation** for urban trees, Barcelona's Tree Master Plan sets a model for effective carbon sink governance that balances environmental, social, and economic benefits. The city complements its strategy with carbon sequestration in wooden buildings, urban agriculture, and blue carbon projects (Posidonia).

The city of Sofia proposes a comprehensive approach to natural carbon sinks (Sofia, 2025). The city's measures include the **rehabilitation and expansion of existing parks, gardens, and green areas**, as well as the **planting of new trees and creation of a green belt** around the city. Additionally, Sofia is developing **new forests**, implementing soil management practices to **improve topsoil** and carbon sequestration, and restoring areas as habitats for various species. The city has also developed a plan to support the **long-term watering of tree vegetation** and other green areas in conditions of prolonged summer and autumn droughts. This plan aims to ensure that trees and shrubs receive adequate water during critical phases of their development in unfavourable climatic conditions. Moreover, each year, **old trees are replaced** by new more appropriate species as per the scientific recommendations, new trees are planted in the city and a new forest is developed to surround the city and protect it from outside harmful emissions impact. Furthermore, Sofia has initiated actions to develop **expert catalogues of trees** and other plant species suitable for urban landscaping and agricultural crops and varieties suitable for use in agriculture given the **expected future climatic conditions**. The city is also implementing

**landscape measures to accelerate tree growth**, including improving soil composition, using compost and natural fertilisers, and optimising the structure of tree massifs and accompanying vegetation.

For each emission or carbon gain factor selected, cities should choose a time over which the factor applies. This is because emissions and removals occur on different timescales. For instance, deforestation events or canopy loss from pruning can be realistically assigned a high emission factor at the time of the event, whereas afforestation or canopy growth/expansion may be better described by a much smaller carbon gain factor applied over many years or decades.

As concerns emission factors, cities may consider using the 20-year transition approach or the "committed" approach (WRI et al., 2022). The former is a process-based method that distributes emissions from land use change over time spreading them evenly across 20 years following land use change (IPCC default assumption). This results in more complex calculations and carrying over emissions from previous inventories (assuming these are available). Conversely, the "committed" approach is an event-based method that assumes full or partial loss of carbon stock at the time of deforestation, disturbance, or loss of tree canopy. This may be a reasonable simplification for cities and reduces the complexity of calculation: the initial emissions overestimation would typically self-correct over time. Further simplification is discussed in **Box 33**.

For carbon gain factors, the timescale of removals associated with NFL converted to FL can be simplified by using an annual factor that reflects the growth[14] of younger stands and by assuming that start date for the new stand and beginning of inventory period coincide (WRI et al., 2022). Subsequent inventories while the biomass continues to grow would be based on the annual carbon gain factor of FL remaining FL and would capture any potential reversal. Similarly, newly detected (or newly detected and maintained) tree canopy outside forests can be assigned a "new growth" carbon gain factor for the relevant inventory period and then an "established" carbon gain factor for subsequent inventories, if distinct carbon factors are available.

Additional guidance on calculating emission and carbon gain factors can be found in (WRI et al., 2022).

**Box 33**. Further simplification: the active growing period

For trees on NFL, an "active growing period" (AGP) may be established based on the average age of the tree population. The IPCC default is 20 years. Both emissions and removals for populations exceeding the AGP may be zeroed on the assumption that increases in biomass carbon would be offset by losses from pruning and mortality. This is a rather coarse approach. The recommendation in the framework of the Cities Mission is to collect data to monitor changes in tree canopy or tree number. Also, Mission Cities shall account for emissions and removals separately.

### 7.1.1.2 Emissions and removals calculation

$CO_2$ emissions and removals associated with forests (F) and trees (T) are calculated as:

$$CO_{2_{net,F\,\&\,T}} = CO_{2_{FL\rightarrow NFL}} + CO_{2_{FL,dist}} + CO_{2_{NFL,loss}} - CO_{2_{NFL\rightarrow FL}} - CO_{2_{FL,undist}} - CO_{2_{NFL,gain}} \qquad (2)$$

[14] Growth functions can be derived from existing data in urban tree cadastres, agricultural schools, breeding centres, or botanical gardens which also may have data for exotic urban tree species.

with $CO_{2_{FL \rightarrow NFL}}$ and $CO_{2_{NFL \rightarrow FL}}$ representing the emissions and the removals from FL converted to NFL and viceversa, $CO_{2_{FL,dist}}$ and $CO_{2_{FL,undist}}$ being respectively the emissions associated with disturbances (e.g., tree harvest for commercial or other purposes) and the removals associated with undisturbed conditions on FL remaining FL, and $CO_{2_{NFL,loss}}$ and $CO_{2_{NFL,gain}}$ indicating the emissions from loss of trees and the removals by gained and maintained trees on NFL. Every term in **Equation (2)** is presented as an absolute value, with the sign of each term indicating whether it represents emissions or removals.

To calculate $CO_{2_{FL \rightarrow NFL}}$ or $CO_{2_{NFL \rightarrow FL}}$, the activity data refer to the total area of FL lost or gained during the inventory cycle respectively. These terms can be calculated for each conversion category separately or regardless of the subsequent/previous land use. It is noted that land use changes should be carefully identified (see **Box 34**).

To calculate $CO_{2_{FL,dist}}$ activity data correspond to the areas affected by disturbances during the inventory cycle. Data on harvest volumes for timber or fuelwood shall be used to estimate emissions for these types of disturbances, while for other types, cities may be required to make some assumptions, based on available data (this may vary greatly on a case-by-case basis). To avoid possible double-classification (and double counting), it is recommended to define areas of land use change prior to areas of disturbance. Indeed, during an inventory cycle, it may happen that the same area is classified as disturbed and converted area (i.e., FL converted to grassland). In these cases, the land use change should take priority so that only FL remaining FL areas are included in the calculation of $CO_{2_{FL,dist}}$. It is also suggested to assign only one disturbance to the same area (e.g., harvest over fire or viceversa), possibly based on a hierarchy of disturbances dictated by the severity of the impact on GHG fluxes.

The activity data for $CO_{2_{FL,undist}}$ is the area of undisturbed forest, calculated as the difference between the total area of FL remaining FL and the total disturbed area (used to calculate $CO_{2_{FL,dist}}$).

To calculate $CO_{2_{NFL,loss}}$ the activity data is the loss of tree canopy, whereas both gained and maintained trees on NFL could be conflated as removals into $CO_{2_{NFL,gain}}$.

Equations and sample calculations for each of the equation terms are provided in (WRI et al., 2022), following the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006, 2019a). The guidance includes also equations, default fire combustion values, and sample calculations for $CH_4$ and $N_2O$ emissions from fires on both FL and NFL. Other non-$CO_2$ sources, such as soil $N_2O$ emissions from mineral fertilisation and organic amendments and $CH_4$ emission from forested wetlands, are not covered. Finally, the guidance provides the links to downloadable spreadsheets with worked sample inventories.

Net emissions for both FL and NFL should be annualised eventually and expressed in $tCO_2$-eq/yr.

**Box 34**. "Correcting" the land use change matrix

Before calculating gross emissions and removals, cities should check whether temporary changes in land cover have been conflated with changes in land use (see **Box 26**). This requires estimating the proportion (0-100%) of the land use change that is considered permanent and re-assigning temporary changes to unconverted land uses (if any). This is based on an understanding of the nature of the process that has provoked the changes in the local environment and typically applies to FL. For instance, if timber harvesting takes place within a managed forest concession, the change in land cover from FL to grassland is likely

temporary and the land use should be corrected to FL remaining FL. Temporary effects may also respond to cyclic events (e.g., of harvest and disturbance followed by forest recovery). Also in this case, no land use change occurs as the land cover change is temporary. In contrast, if forest trees are removed to accommodate an expanding urban population, the associated land cover change likely reflects a change in land use. It is worth recalling here that afforestation and reforestation practices are associated with land use changes, whereas regeneration practices are associated with FL remaining FL (as discussed in **Annex 1**).

For NFL (i.e., non-forest trees), corrections are generally not needed since tree canopy changes are not associated with a land use change.

Any necessary corrections should be properly documented and reported in the CNAP.

### 7.1.2 Wetlands

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) and the 2013 Supplement dedicated to Wetlands (IPCC, 2014b) are the main source of guidance currently available in dealing with anthropogenic emissions and removals of GHGs (notably $CO_2$, $CH_4$, and $N_2O$) associated with wetlands. Compared to the 2006 guidelines, the Wetlands Supplement fills important gaps in coverage (wetland types) and provides updated information reflecting scientific advances, including on emission factors. The emissions and removals from wetlands and drained soils addressed in the Wetlands Supplement i) can occur under any land use category or other relevant category (i.e., not just in the dedicated wetland category), ii) may occur both when the land remains the same type of land and when it gets converted into another type, and iii) cover both inland and coastal land as well as both organic soil (drained/wet) and mineral soil (drained/wet). Notably, the Supplement deals with:

- **Drained Inland Organic Soils**: managed inland organic soils including land drained for forestry, croplands, grazing, and settlements across climate zones.
- **Rewetted Organic Soils**, including boreal, temperate, and tropical wetlands occurring in any land use category.
- **Coastal Wetlands**: specified management activities in coastal areas of mangroves, tidal marshes and seagrass meadows.
- **Inland Wetland Mineral Soils (IWMS)**: managed inland wetland mineral soils, including lands used for forestry, cropland, grazing, and settlements, and rewetted mineral soils. Included activities are i) artificial drainage of IWMS (ii) subsequent rewetting of artificially drained IWMS and (iii) artificial flooding of mineral soils for the purposes of wetland creation. Mineral soil wetlands include riparian wetlands, forested swamps and marshes and can occur in all climate zones.
- **Constructed Wetlands for Wastewater Treatment**, i.e., wetlands that have been designed and constructed to use natural (or semi-natural) processes involving vegetation, soils, and associated microbial assemblages to treat wastewater.

This is complemented by the 2006 guidance on i) peatland managed for peat production, ii) rice cultivation, and iii) permanently flooded lands, in (IPCC, 2006). Conversely, the IPCC has not yet provided guidance on saline inland wetlands (i.e., playas, pans, salt lakes, brackish wetlands, salinas, and sabkhas). Key definitions are provided in **Box 35**, while **Figure 7** shows the decision tree to determine which guidance is best suited and the relevant chapters.

**Box 35**. Key definitions (adapted from (IPCC, 2014b))

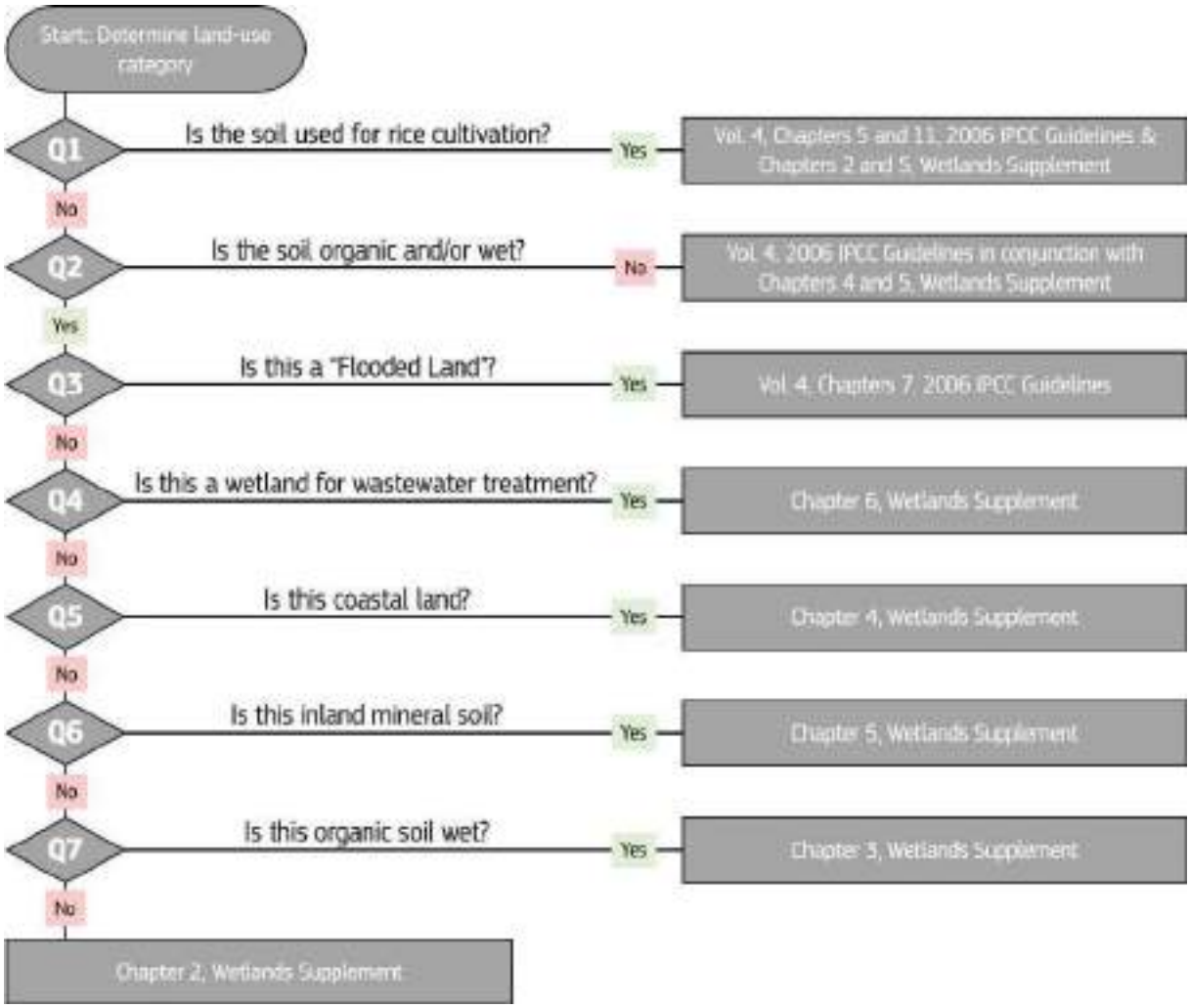
A wet soil is a soil that is inundated or saturated by water for all or part of the year to the extent that biota, adapted to anaerobic conditions, particularly soil microbes and rooted plants, control the quality and quantity of the net annual GHG emissions and removals. Every soil that is not a wet soil is classified as a dry soil in the Wetlands Supplement.

Drainage is the process of artificial lowering of the soil water table. In the Wetlands Supplement, the term is used to describe the act of changing a soil from wet into dry. A drained soil is a soil that has formerly been a wet soil, but as a result of human intervention has become a dry soil. All organic soils (e.g., marshes, bogs, and swamps) are assumed to have originally been wet, therefore a dry organic soil is always also a drained organic soil.

Rewetting is the process of changing a drained soil into a wet soil. A rewetted soil is a soil that has formerly been a drained soil but as a result of human intervention has become a wet soil. Similarly, wetting is the process of changing an originally dry soil into a wet soil as a result of human intervention, as in wetland creation.

Restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed. In the case of former drained wetlands, restoration always includes rewetting.

**Figure 7.** Decision tree for finding the appropriate guidance chapter within the Wetlands Supplement or the 2006 IPCC Guidelines




*Source: adapted from (IPCC, 2014b)*

In line with the general IPCC approach, estimation methods are provided at three levels of detail, from Tier 1 (the default method) to Tier 3 (the most detailed method). In the Wetlands Supplement, emission factors are updated and new GHG sources are included in Tier 1 guidance (e.g., $CH_4$ emissions from drained land and drainage ditches and $CO_2$, $CH_4$ and CO emissions from peat fires - both wildfires on drained peatlands and managed fires). Additional Tier 1 guidance is given to include the impact of drainage depth (watertable level) and nutrient status on $CO_2$, $CH_4$ and $N_2O$ emissions (Institute for European Environmental Policy, 2015). The guidance also applies to partly rewetted conditions where the water table has been raised but has not reached the near-natural status. The Supplement's Annexes describe the methodological background for deriving the emission factors so that they can be traced back to check to what extent they are representative of local conditions. Activity data vary largely depending on the restoration project; however, potential challenges and barriers are identified in finding activity data with comparable quality for drainage and rewetting measures and the water table status in general.

Cities are encouraged to familiarise with the IPCC guidance when including wetlands restoration in their residual emissions strategy. In addition to the IPCC guidelines, cities can refer to various

reports and standards that provide further guidance on wetlands restoration accounting. Some notable documents include:

— The Verified Carbon Standard (VCS) Wetlands Restoration and Conservation methodology, which provides detailed guidance on accounting for wetlands projects (Needelman et al., 2018).

— The Ramsar Convention's "Wetlands and Climate Change" guidance document that offers insights into the role of wetlands in climate change mitigation and adaptation (Ramsar, n.d.). It comes with a Global Wetland Outlook which provides an overview of the status and trends of wetlands globally, including their carbon sequestration potential.

Accounting for the positive and negative emissions associated with wetlands restoration requires a comprehensive approach that considers various factors (see **Box 36** and **Box 37**). Here are some steps cities can take in this exercise:

— Establish a baseline: cities should determine the current state of wetlands and their associated emissions. This includes assessing the carbon stocks, GHG emissions, and other relevant environmental factors.

— Identify restoration goals: cities should define their wetlands restoration objectives, such as increasing carbon sequestration, enhancing biodiversity, or improving water quality. These goals will help guide the accounting process.

— Assess restoration activities: evaluate the specific restoration activities planned or implemented, such as reforestation, rewetting, or invasive species removal. Determine the potential positive and negative emissions associated with each activity.

— Quantify emissions: use established methodologies and guidelines to estimate the emissions associated with wetlands restoration.

— Consider co-benefits: wetlands restoration often provides additional benefits beyond emissions reduction, such as flood mitigation, habitat creation, or recreational opportunities. Consider these co-benefits in the accounting process to provide a more comprehensive assessment.

**Box 36**. A comprehensive look at wetlands restoration

When wetlands restoration is included in the residual emission strategy, cities should be consistently looking across the overall trend in wetlands evolution within the geographical boundary. All areas where drainage has become deeper or shallower should be accounted for to avoid a biased perception of the net effect of this natural ecosystem on GHG emissions. In other words, it is not sufficient to track only wetland restoration where GHG emissions have been reduced or GGR has been achieved. All wetlands should be monitored in a comprehensive way so that drainage measures are tracked as well (Institute for European Environmental Policy, 2015). In terms of drainage status, the Wetlands Supplement distinguishes between undrained, shallow drained and deep drained status. Cities should develop maps with spatially explicit information on peat type, nutrient status, water table and land use to produce a spatially explicit stratification of wetlands by drainage status. Continued observations could help establish a time series of drainage status and design policies and actions accordingly. The drainage status can also be based on dip-well data, climate, land use, peat properties and topographic position to produce maps which in turn can be used to derive area-weighted average emission factors per land use category (Bechtold et al., 2014).

Similarly, all the steps of wetlands restoration should be accounted for. Wetland restoration and management can involve i) technical large-scale measures (including the installation of ditches for rewetting or the cutback of dykes to enable flooding) and ii) technical small-scale measures such as clearing trees; changes in land use and agricultural measures, such as adapting cultivation practices in

wetland areas[15]. These processes are themselves sources of emissions and their impact should be transparently quantified.

On another note, some degraded peatlands have become secondary habitats for endangered species which has led to the water table being managed, for example, for bird protection. This can have partial benefits in terms of GHG emissions but may be critical in terms of biodiversity conservation. In this case, restoration may come with greater negative impacts than benefits overall.

**Box 37**. The dynamic ecosystem of coastal wetlands

Coastal wetlands (tidal marshes, or salt-marshes) are saltwater and brackish water wetlands located in coastal areas. Coastal wetlands also include areas of marine water the depth of which at low tide does not exceed six metres (Ramsar, n.d.). They include shallow water ecosystems permanently or periodically inundated and intertidal habitats (Climate ADAPT, 2023). Coastal wetlands differ from land ecosystems because they have highly dynamic matter exchange in both horizontal and vertical directions, which can originate from natural and anthropogenic processes or - most commonly - a mixture of both (Institute for European Environmental Policy, 2015). Chapter 4 of the Wetlands Supplement provides methodologies to estimate how human activities, management practices and land uses affect emissions, e.g., how the restoration, creation, and recovery of wetlands affect carbon sequestration and GHG emissions. The lifetime of restoration interventions of coastal wetlands depends on local conditions, in particular erosion and sedimentation processes and on the strategy implemented. Regular maintenance may be required to keep wetland conditions, considering that they are naturally unstable and ever shifting ecosystems (Climate ADAPT, 2023).

## 7.2 The built environment

The buildings and construction sector are not only a major source of greenhouse gas (GHG) emissions, but they also hold untapped potential as a carbon sink. When buildings are constructed with bio-based materials (e.g., timber, hemp, straw), they can act as mid- to long-term carbon reservoirs by storing the biogenic carbon that was absorbed from the atmosphere during plant growth. This effectively embeds atmospheric $CO_2$ in the built environment for the lifespan of the building. For example, a five-story mass timber building can store around 180 kg of carbon per square meter of floor area. This is about three times the carbon density of a natural forest with high biomass (Churkina et al., 2020; European Parliament and Council, 2024c; Partners for Innovation & Wageningen University and Research, 2024). Because buildings are typically long-lived assets (often 50-100 years or more in service), carbon stored in them can be considered long-duration (but not permanent) removal. The EU's push toward Whole Life Carbon accounting in buildings in the revised Energy Performance of Buildings Directive (EPBD) and the Carbon Removal and Carbon Farming (CRCF) Regulation set the foundation for a clear methodology for acknowledging the carbon stored in the built environment (European Parliament and Council, 2024c, 2024b).

The CRCF Regulation, establishing a Union certification framework for permanent carbon removals, carbon farming, and carbon storage in products, explicitly recognises and prioritises methodologies for carbon storage in wood-based and bio-based construction products. This activity is fundamentally contingent on the use of materials that are net carbon negative at the point of

[15] A list of wetlands restoration projects can be found here for reference.

installation and remain durably stored in the building for at least 35 years. Such long-term use of harvested biomass in products is deemed more climate-beneficial than short-term applications or direct combustion without carbon capture and storage. Notably, the CRCF foresees group audits or groups of operators, so while the initial building methodology targets single-building projects, it is intended to also accommodate grouped certifications at a later stage. The methodology is currently being developed by the European Commission with the aim to be finalised in 2026. Cities can already pilot building-level MRV compatible with CRCF and design data systems that can ingest methodology outputs once delegated acts are adopted.

Realising this potential presents several significant challenges concerning MRV complexity, data gaps and liability. Accurate quantification of net carbon removal in buildings requires robust methods for calculating baseline carbon removals, total carbon removals of the activity and associated greenhouse gas emissions over the entire lifecycle. There is a recognised need for clear, simplified rules to quantify biogenic carbon stored in bio-based construction products, especially since widely accepted standards like EN 16449 and EN 16485 primarily cover wood-based products, leaving a gap for other bio-based materials. Baselines also vary significantly by building typology and region, making a single standardised baseline difficult to establish. Furthermore, accurately monitoring, reporting, and verifying carbon storage in buildings is challenging due to the diversity of materials and construction practices, and limited data. Buildings are made with a mix of e.g., timber, concrete, metals, composites and the carbon content of bio-based elements can vary widely. This is data that cities often do not systematically collect. Material inventories at the urban scale are just beginning to be developed. At the same time, the revised EPBD Directive and the revised Construction Product Regulation mandate the establishment of systems for building material passports, digital logbooks or requirements to report material use by 2030.

Storage is long-lived but not permanent: fire, decay, demolition, or sub-optimal end-of-life treatment can release stored carbon. CRCF will pair storage-duration requirements with liability for reversals; city inventories should mirror this with risk buffers and/or stock-difference accounting. Operators are legally liable for such reversals during the monitoring period. Effective liability mechanisms, such as collective buffers or upfront insurance, are therefore critical for credibility. These challenges shall be addressed through robust accounting approaches, which we outline below, alongside strategies to maximise the benefits and manage the risks of treating buildings as part of a city's carbon balance.

Despite the challenges, the benefits are compelling. Recognising and accounting for carbon storage in buildings can catalyse a shift to sustainable materials. Cities that include building carbon sinks in their climate plans can thereby address an often-overlooked wedge of emissions and removals. Importantly, utilising biomass residues and sustainable timber in construction can be a relatively cost-effective carbon removal strategy, since the cost of $CO_2$ removal is partly covered by the value of the building product itself (RMI, 2025). Moreover, framing buildings as carbon sinks can open new financing opportunities. For instance, carbon credits or certificates that monetise the stored $CO_2$ could provide revenue to projects. Initiatives like "Construction Stored Carbon" certificates are already emerging to fund the transition to bio-based construction by monetising the climate value of stored carbon (Climate Cleanup, n.d.). Lastly, empowering cities to track and increase carbon storage in buildings aligns with European climate objectives and innovation agendas. It ties together climate mitigation with the circular economy, sustainable forestry, and the bioeconomy.

Overall, incorporating buildings as carbon sinks in urban climate accounting is challenging but offers a scientifically grounded, policy-aligned, and potentially high-impact new lever for cities to achieve their climate targets.

### 7.2.1 Accounting principles and GHG estimation methods

City-level accounting of carbon storage in buildings shall follow fundamental GHG accounting principles: consistency, transparency, accuracy, completeness, and comparability (IPCC, 2019a). These should be complemented by the quality criteria of the Carbon Removal Certification Framework (CRCF), discussed below. Adapting these to city-level contexts ensures that building-related removals are both credible and policy-relevant.

Under the CRCF Regulation, carbon storage in buildings can be certified as a temporary net carbon removal activity (European Parliament and Council, 2024b). The framework applies to activities that capture and store atmospheric or biogenic carbon in long-lasting products for a minimum of 35 years, with on-site monitoring requirements throughout this period (Article 12). Certified outcomes take the form of verified traceable $CO_2$-removal units attributable to individual buildings.

The European Commission's Technical Assessment Paper (TAP) specifies that the first methodology under development focusses on long-term biogenic storage in construction products such as structural timber, bio-based panels and insulation materials (Partners for Innovation & Wageningen University and Research, 2024). Draft elements of the methodology are being refined within the CRCF expert group process, with finalisation targeted for 2026. Importantly, the Regulation allows certification by "an operator or a group of operators" (Article 8), enabling grouped certifications (for instance, multiple buildings under a single city programme) once the methodology is operational. This feature is particularly relevant for cities aiming to scale carbon storage across portfolios.

While the CRCF building methodology is still being developed, it rests on four interlinked QU.A.L.ITY criteria (Quantification, Additionality, Long-term storage, and SustainabilITY, see **Section 9**) along with transparency. These are outlined below:

— **Quantification**. Cities should employ robust, transparent and conservative quantification methods, documenting data sources (e.g., material intensity coefficients, construction permits) and explicitly addressing uncertainties through ranges or error margins. Importantly, accounting shall include all relevant GHG fluxes. In practice, this means that when calculating net removals, emissions from material processing, transportation, or construction activities are deducted from the gross carbon storage (Partners for Innovation & Wageningen University and Research, 2024). Where detailed lifecycle assessments (LCA) are not feasible at city scale, default coefficients used in inventories should ideally represent net values that already account for typical upstream emissions. This prevents overestimation of removals. Furthermore, double counting shall be avoided: if a building's stored carbon is claimed in the city inventory but also sold as a carbon credit to a company, the same unit would be claimed twice. Cities should establish clear governance rules to define whether removals are counted toward city targets, national inventories, or external offsetting, and should reference registries (e.g., the CRCF registry) where appropriate to ensure transparency.

— **Additionality**. At the building level and for crediting processes, the CRCF certification requires proof that removals are additional, i.e., they would not have occurred without the specific project or intervention (European Parliament and Council, 2024b). Translated to the city scale, this means emphasising policy-driven gains rather than re-labelling existing stock. For example, if a city introduces incentives for timber construction, the additional storage compared to a "business-as-usual" baseline should be highlighted. While inventories can report all stored carbon, credible target-setting and climate claims should focus on incremental removals attributable to municipal action. This ensures that cities are not simply counting existing practices but demonstrating genuine climate impact.

— **Long-Term Storage (Permanence)**. Carbon stored in buildings is inherently temporary, as materials may be released at end-of-life or through disturbances (e.g., fire, demolition). To address this, cities should adopt conservative permanence assumptions:

  - Duration thresholds. Following CRCF logic, only carbon stored for a minimum period (e.g., 35–50 years) can be fully credited.
  - Reversal adjustments. Inventories should record emissions when stored carbon is released (e.g., demolition without reuse). Alternatively, cities may apply default decay factors (e.g., 1% annual stock reduction) or establish buffer pools of unclaimed removals to insure against reversals.
  - Design and end-of-life practices. Cities can improve permanence by promoting adaptive building design, encouraging the reuse of wood components in new construction or diverting end-of-life biomass into long-lived carbon pools (e.g., biochar, composites).

The temporal characteristics of carbon storage in buildings shall be explicitly recognised. One tonne of $CO_2$ stored in biogenic construction materials cannot be considered equivalent to one tonne stored in geological formations over millennial timescales. Rather, urban carbon storage represents a mid-term mitigation measure, with a typical duration of several decades. It provides meaningful value within the 2030–2050 climate neutrality horizon, but its contribution is contingent on implementing strategies that either extend storage duration (e.g., reuse, cascading applications) or substitute it with more permanent removal options over time.

— **Sustainability.** Efforts to enhance carbon storage in buildings shall not generate adverse environmental or social side-effects. This principle aligns closely with the European Union's sustainability criteria, including those under the EU Taxonomy Regulation and the CRCF Regulation, which require that carbon farming and product storage activities deliver a neutral or positive impact on biodiversity, ecosystems, and social safeguards (European Parliament and Council, 2024b). At the building scale, this means carbon storage should only be credited where materials are sourced sustainably. For bio-based construction, timber and other biogenic inputs shall come from certified sustainable forestry or agriculture that avoids deforestation, biodiversity loss, and land-use conflicts (e.g., food displacement). Recognised certification systems such as FSC and PEFC provide credible assurance of sustainable sourcing. Using unsustainably harvested wood, such as clear-cutting carbon-rich forests, may create immediate storage in the building but simultaneously cause a net reduction in forest carbon stocks, thereby undermining the climate benefit and violating the additionality principle (Partners for Innovation & Wageningen University and Research, 2024). In addition, sustainability extends to circularity considerations. The climate benefit of stored carbon is maximised when buildings are designed for reuse, modularity, and recycling, ensuring that bio-based materials continue to act as carbon reservoirs after the initial building's end-of-life. This is consistent with the EU Circular Economy Action Plan and the Level(s) framework, which encourage life-cycle thinking and resource efficiency in construction (European Commission, 2020a).

— **Transparency**. Given the novelty of building-related carbon storage in urban climate inventories, cities should adopt a transparent approach in methodological documentation and reporting. At minimum, cities shall:

  - report the accounting method, data sources, and assumptions (e.g., material coefficients, lifespan assumptions, or sustainability criteria).
  - Report carbon removals separately, rather than directly netted against operational emissions (see **Section 6.2**).

  As methodologies mature, particularly with the finalisation of the CRCF methodology for carbon storage in buildings (expected by 2026), cities can gradually align their reporting with EU-wide registries and standards, facilitating comparability across jurisdictions.

Such practices ensure that cities are credible and transparent actors in the early adoption of carbon storage accounting, while providing flexibility for future alignment with EU regulations (see also **Box 38**).

**Box 38.** Using building-level CRCF data in city accounting

Once individual buildings have been quantified under the CRCF methodology or a similar recognised certification scheme, cities could integrate this information into their climate inventories in several ways:

— **Direct aggregation of certified units**. Where multiple buildings have undergone certification, the city may sum the verified $CO_2$-removal units from those projects to report the total carbon storage contribution from the building sector. This pathway would ensure robustness, transparency and avoidance of double counting. It effectively embeds bottom-up MRV results into city-level accounting.

— **Proxy estimation via building registries**. Not all buildings may undergo certification. Nevertheless, municipalities can use permit data, building registries or digital logbooks to identify new buildings likely to contain significant amounts of stored biogenic carbon. In many cases, permitting processes already require disclosure of the structural system or submission of a life-cycle carbon assessment. When a

new development is known to be timber-based, the city could apply removal factors calibrated from certified projects. In this way, the rigour of certified projects provides benchmark values that can be extended, cautiously, to non-certified stock.

— **Continuous benchmarking and model refinement**. Bottom-up certification data also provides empirical benchmarks that can improve the accuracy of city-wide, top-down models. Over time, as the CRCF registry and EPBD accumulate data across building typologies and climatic regions, municipalities will have access to a growing evidence base to refine assumptions and reduce uncertainties in their inventories.

The present scope of the CRCF Regulation is limited to biogenic carbon storage and does not extend to mineral carbonation in building materials. Nevertheless, a range of innovative technologies are emerging where $CO_2$ is chemically bound into construction materials, such as $CO_2$-cured concrete blocks or synthetic aggregates that permanently embed captured $CO_2$. As the science, standards, and certification frameworks evolve, extensions of EU methodologies to cover mineral carbonation in construction may emerge.

### 7.2.2 MRV and data systems for carbon removals in buildings

Robust monitoring, reporting, and verification (MRV) systems are critical for integrating the carbon storage potential of buildings into city-level climate accounting. The credibility of negative emission claims depends on the quality, completeness, and transparency of underlying data. While the CRCF is establishing a registry and methodological standards at the project level, cities will need to develop complementary systems to capture, aggregate, and monitor stored carbon across their building stock:

— **Material passports and digital building logbooks.** A central innovation is the introduction of material passports, i.e., digital records of the type and quantity of construction materials embedded in a building. These passports, which are promoted under the EU Circular Economy Action Plan and initiatives such as Level(s), can document the biogenic carbon stored in structural timber, insulation and other bio-based materials. Digital building logbooks, referenced in the revised Energy Performance of Buildings Directive, provide a broader repository, combining information on energy performance, retrofit history and material composition. Coupled with Building Information Modelling (BIM) enriched with material property data, these systems can be scaled to city databases, allowing local authorities to aggregate carbon storage data across multiple projects. Pilot initiatives such as BAMB – Buildings as Material Banks (BAMB, n.d.) have demonstrated the feasibility of embedding such systems into construction and renovation workflows.

— **Urban material registries.** Cities can establish urban material registries that consolidate data from building permits, embodied carbon reports or national renovation plans. Several Member States already require whole-life carbon assessments for new construction (e.g., France, the Netherlands, Denmark), which can provide the necessary input data (Partners for Innovation & Wageningen University and Research, 2024). Linking permitting processes to mandatory reporting of material use ensures consistent data collection. Over time, registries become essential for dynamic stock-difference accounting, helping cities model both inflows (new bio-based construction) and outflows (carbon released during demolition). Where direct data are unavailable, remote sensing, typology mapping and partnerships with universities can help approximate material distributions in the legacy building stock.

— **Standardised coefficients and default values.** In the absence of detailed data, cities should rely on standardised coefficients for carbon storage per building type (e.g., $kgCO_2$ stored per square metre of floor area). Values can be drawn from established databases such as ecoinvent, the Inventory of Carbon and Energy (ICE), or national LCA datasets. Harmonisation is critical: all departments and consultants should use the same set of default values to ensure consistency and comparability. These coefficients should be documented in a methodological annex and periodically refined as more precise data (e.g., from CRCF-certified projects or national inventories) become available.

— **Integration with EPBD and renovation strategies.** The recast EPBD (European Parliament and Council, 2024c) strengthens the role of material carbon accounting. Annex II requires Member States to report policies addressing whole life-cycle emissions, including carbon removals in buildings. Annex V allows for the inclusion of carbon storage information in Energy Performance Certificates (EPCs), creating a potential city-level data source. By aligning local MRV with these national processes, cities can ensure coherence and reduce duplication. Moreover, cities can link renovation programmes with carbon storage strategies, for example, promoting bio-based insulation materials that both enhance energy efficiency and increase stored carbon.

— **End-of-life and waste reporting.** Cities should connect material flow data from construction and demolition waste reporting with their carbon stock models. For instance, tracking how much wood waste is incinerated, recycled or landfilled provides critical insights into how much stored carbon is released versus retained in secondary products. This integration is consistent with circular economy objectives and ensures that removals are not overestimated.

— **Verification and audits.** Given resource constraints, cities are not expected to verify every building. Instead, they can adopt sample-based audits, applying CRCF-style verification to a subset of buildings. These audits can check whether default coefficients align with real-world data and adjust methodologies accordingly. This mirrors national approaches to land sector inventories, where sampling and stratification are used to manage uncertainty (IPCC, 2019a).

— **Public registries and transparency.** By 2028, the CRCF Regulation will establish an EU-wide public registry of certified removals. Cities could complement this with their own transparency portals, highlighting carbon-storing projects within their boundaries. For example, mapping neighbourhoods with high timber construction or reporting annual additions to stored carbon stock could enhance citizen awareness and political accountability. Public-facing communication of removals would also help build trust and legitimacy in this emerging domain.

## 7.3 Estimating and managing uncertainty in accounting

The arena of emissions compensation measures is wide and highly heterogeneous (consult the **Annexes**). Especially when it comes to permanent sinks, maturity, time and cost-effectiveness (see **Section 6.6**), feasibility, challenges for certification, scalability, transferability, replicability, and sustainability are critical aspects to consider when weighing co-benefits versus risks and adverse impacts. These may vary significantly (and, in some cases, unpredictably) across different options. Research and pilots on CDRs are still insufficient to reduce uncertainty and optimise business performance to a level that makes these technologies not just marketable, but implementable on a large scale. Practical constraints exist, protocols and standards are emerging but are not yet trained enough. Further, skills may go beyond the municipal experience and expertise, thus calling for

specific capacity-building, partnerships, and effective communication to reduce uncertainty over city-driven implementation and management.

Temporary carbon sinks and carbon credits also come with distinctive sources of uncertainty. Nature-based carbon sinks are often associated with uncertainties in data sources and measurements, permanence (e.g., vulnerability to disturbances), and carbon leakage. In the specific cases of wetland restoration and soil carbon sequestration, a significant source of uncertainty is associated with the potential release of methane and nitrous oxide, which may cause a temporary warming effect. The magnitude and time horizon for these effects are cast in uncertainty and call for dedicated research and careful monitoring. This is particularly pressing when working against a 2030 deadline, as requested of Mission Cities. There are uncertainties also in the decomposition rates of the various types of biochar depending on the pyrolysis feedstock and temperature (The Royal Society, 2018). Carbon credits may come with uncertainty over environmental integrity principles (**Table 4**), notably those most difficult to prove, such as additionality.

To navigate and lower the various sources of uncertainty, cities are encouraged to regularly check the availability of existing protocols such as guidance documents, performance standards, accounting equations, formulas, and/or methods. Yet, since most of the uncertainty stems from limited testing and knowledge-creation around carbon removal options, cities (with Mission Cities at the forefront) and their Member States are called upon creating the demand for projects, technologies and solutions that are net-zero aligned. Market signalling and demand creation for long-lived storage will help reduce uncertainty over time and accelerate deployment. This would guarantee the necessary supply over the long-term (M. Allen et al., 2020). Finally, local and national authorities should contribute with documentation and testing of accounting procedures. This is particularly pressing when taking into account the contribution of land use change to GHG emissions in connection with exploitation of land. There is also a pressing need to i) increase the robustness of monitoring, reporting and verification, ii) enhance transparency, comparability and competition between different carbon removals activities, iii) level the playing field of voluntary carbon markets, and iv) provide better public incentives for nature-based and technological removals (European Parliament and Council, 2024b). Finally, establishing comprehensive quality requirements for carbon removals would ensuring correct quantification of carbon removals, additionality, long-term storage and environmental sustainability.

Uncertainties in the quantification of positive and negative emissions associated with carbon removals should be acknowledged and possibly accounted for via statistical means in order to limit the risk of over- or under-estimating the impact of emissions compensation measures.

A high level of accuracy is especially recommended where compensation mechanisms impact critical resources (e.g., land, water) whose availability is limited and whose uses are multifold and potentially competing. This is a necessary condition to protect and enhance the resilience of urban and natural ecosystems. However, identifying, understanding and reconciling disparate data sources may be one of the most challenging and time-consuming steps of emissions accounting, especially when negative emissions from the land sector are concerned.

To estimate uncertainty, cities should design a workable process to keep track and qualify (possibly quantify) the many potential sources of error, based e.g., on the 'probability of exceedance" approach (see **Box 39**). A simplified method to combine (or "propagate") uncertainty with specific formulas to develop a quantitative estimate can be found in (IPCC, 2006, 2019a). Another possible approach is described in the GPC Section 5.6 (WRI et al., 2022), in which the quality of activity data and emission/carbon gain factors is assessed as high, medium, or low, based on i) the degree to

which data used reflect the geographical location of where they are applied, and ii) whether data have been obtained from reliable and verifiable source (**Table 11**). This qualitative assessment (that largely corresponds to the Tier 1-3 approaches established by the IPCC) may also inform monitoring activities in view of progressively reducing uncertainty. Further, customised accuracy assessments can be implemented to improve the local area estimates of activity data based on national inputs, as performed in (Olofsson et al., 2014) for land change data. As a minimum requirement, cities should determine whether the uncertainty in their calculations would most likely cause under- or over-reporting. This would be critical in designing action plans that can more readily and flexibly respond to adjustments.

**Table 11.** Grading data quality to ease the estimation of uncertainty

| Data quality | Activity data | Emission or Carbon Gain Factor |
|---|---|---|
| **High** | Detailed local activity data | Local emission / carbon gain factors |
| **Medium** | Modeled activity data using robust assumptions | More general emission / carbon gain factors (e.g., national factors) |
| **Low** | Coarsely modeled or uncertain activity data | IPCC default emission / carbon gain factors |

*Source: JRC analysis (adapted from (WRI et al., 2022)).*

**Box 39**. Probability of Exceedance to manage uncertainty

Probability of Exceedance is a suitable approach for statistical uncertainty estimation in carbon removals, used by e.g., the IPCC. This method allows for the quantification of the likelihood of surpassing certain levels of carbon removal, providing decision-makers with a clearer understanding of potential outcomes and associated uncertainties. The approach involves several steps:

- Data collection on sequestered carbon from e.g., empirical studies, field measurements, or modelling simulations.
- Distribution fitting, which involves fitting a probability distribution function to the data to characterise the variability and uncertainty in carbon removal estimates.
- Probability estimation to determine the likelihood of surpassing a specific level of carbon removal.

In addition, a sensitivity analysis may be conducted to identify key factors that influence the uncertainty in carbon removal estimates. This step helps to prioritise areas for further research or data collection to improve the accuracy of uncertainty assessments.

To manage uncertainty (and possibly decrease the costs of establishing baselines, monitoring, and reporting emissions), cities should make use of available (and accurate) digital technologies, including electronic databases, geographic information systems (GIS), remote sensing[16] or airborne mapping (e.g., colour-infrared, orthophotos) and on-site monitoring sensing, artificial intelligence and machine learning, and electronic maps (see also **Box 40**). Map-based approaches are especially recommended for the land sector, so that land use and land use change come with spatial attributes that allow for the co-location with disturbances, emissions and carbon gain factors, and (place-based) urban policies. Map-based approaches may reduce uncertainty and risks of non-

[16] For instance, LIDAR ('LIght Detection And Ranging' or 'Laser Imaging, Detection and Ranging' technology) data are available in many Member States and have been used for digital elevation mapping. They also allow the crown cover and tree height of urban trees or trees outside forests to be estimated.

exhaustive or non-exclusive reporting as compared to sample-based approaches[17] (see **Section 7.1**). Map-based approaches leverage the additional value that geospatial information (e.g., automated processing of satellite data, manual delineation of aerial imagery, and participatory community mapping) can provide for place-based mitigation planning and emissions reporting. This approach may also be more accessible to cities (as georeferenced data may be available through national/regional projects) and may support a more equitable approach to e.g., increasing tree cover, which would reduce the risk of green gentrification during the transition to climate neutrality.

Overall, cities are encouraged to have geographically explicit information to identify priority areas that have the potential to contribute to climate action. They should make the best use of existing Union and Member State programmes and surveys including the Land Use/Cover Area frame Survey ('LUCAS'), the European Earth observation programme Copernicus, the European satellite navigation system Galileo for data collection, the Global Human Settlement Layer (GHSL), and the digital data collected under the Common Agricultural Policy. This would contribute to the digital transition that underpins the Cities Mission. Data management, including sharing of data for reporting, reuse and dissemination, should conform to the requirements provided for in Directive 2007/2/EC of the European Parliament and of the Council (European Parliament and Council, 2007) and should ensure consistency with the national GHG inventories whenever possible. Further, cities should encourage the setup of local maps, databases, detailed land use or agricultural statistics, peatlands and tree cadastres (including information on e.g., species, age, breast height diameter, tree height[18]) while focusing on harmonising and refining databases of activity and emissions/carbon gain factors. This would help improve GHG inventories from one inventory cycle to the next, ensure that the effects of climate policy and actions can be fully reflected over time, and assist in early detection of reversals (**Box 40** and **Box 41**).

**Box 40**. Measuring urban emissions fluxes: the ICOS Cities project and beyond.

Measuring the amount of $CO_2$ that cities emit and absorb is a challenging task. Various techniques exist, such as $CO_2$ monitoring flux towers, ground-based remote sensing, in-situ atmospheric concentration measurements, and satellites.

One of the challenges is that cities have a mix of emission fluxes from human activities (like vehicles and industries) and from plants and trees (like parks and gardens). Researchers, as those involved in the ICOS Cities project, are working to separate these two sources of emissions and understand how plants and trees can help cities towards evidence-based net-zero targets. To achieve this, they are using methods such as footprint modelling (Stagakis, Feigenwinter, Vogt, Brunner, et al., 2023), wavelet analysis combined with carbon monoxide tracers (Coimbra et al., 2025; Herig Coimbra et al., 2025), and field measurements in parks and gardens combined with calibrated local models (Stagakis, Bignotti, et al., 2025; Stagakis, Brunner, et al., 2025).

In Mission Cities like Munich and Paris, which are part of the ICOS Cities project, researchers are using $CO_2$ monitoring towers, atmospheric concentration measurements, and field measurements in urban parks to quantify emissions and understand how plants and trees can help compensate for residual emissions. Additionally, satellite-driven vegetation models, such as the Vegetation Photosynthesis and Respiration Model (VPRM) (J. Li et al., 2025), are being used to estimate biological $CO_2$ fluxes at the city scale. For

[17] Sample-based approaches consist in identifying statistically meaningful samples of points within the geographic boundary and examining them to produce e.g. land use and land use change area statistics.

[18] Sometimes only large trees are included, which would underestimate the sink strength.

example, in Munich, researchers found that the hourly biogenic flux can compensate up to 100% of anthropogenic emissions in the summer afternoon. However, given the respiration in winter and at night, the yearly total biogenic flux only compensates for a few percent of the annual anthropogenic emissions (J. Li et al., 2025). In Basel, the diFUME model has been used to quantify urban biogenic $CO_2$ fluxes, following a semi-empirical approach that integrates meteorological data with high-resolution urban vegetation morphology and leaf area index (LAI) (Stagakis, Feigenwinter, Vogt, & Kalberer, 2023).

By using these techniques, cities can get a better understanding of the contribution of their measures to both emissions reduction and compensation and develop effective strategies and MRV frameworks.

**Box 41**. Monitoring and mitigation of reversals

The carbon stored in natural sinks such as forests may be released into the atmosphere through forest fires, changes in land use or logging. In their action plans, cities should discuss specific measures to ensure the conservation or enhancement, as appropriate, of all carbon sinks and reservoirs, to reduce their vulnerability to ecosystem perturbations driven by climate change, and to create adequate buffers. This is aligned with Article 13b of the amended LULUCF Regulation (European Parliament and Council, 2023b) – see **Section 9**.

This approach would contribute to reducing the overall uncertainty associated with the residual emissions strategy, as ensuring permanent sequestration is key to avoid claiming a climate-neutral status today and losing it tomorrow.

**Cities in the spotlight: Dublin (Ireland), Zaragoza (Spain), Helsingborg (Sweden), Leuven (Belgium), Mannheim (Germany), Lahti (Finland), Greater Dunkirk (France), Trikala (Greece), Trondheim, Stavanger (Norway), Rzeszow (Poland) and Zagreb (Croatia).**

In their CNAPs, Mission Cities demonstrate various MRV options, including mapping, cadasters, on-the-ground monitoring, remote sensing, and citizen science initiatives.

Dublin proposes advanced monitoring of local carbon sequestration through the **Urban Sense** pilot project, which has deployed 20 sensors across the city to measure greenhouse gases, air quality, and weather variables in real-time (Dublin, 2025). This initiative is part of the broader Terrain AI research collaboration, which aims to develop **innovative AI and computational methodologies** to improve the measurement, monitoring, verification, and reporting of carbon stocks and emissions across complex environments. The project's focus on providing accurate estimates of carbon fluxes and identifying cost-effective policies will enable the city to maximise co-benefits and demonstrate the potential of climate action initiatives through digital twinning.

Zaragoza's plan includes a strategy to map the city's green spaces, forests, and tree populations by leveraging remote sensing technology to assess their capacity to absorb $CO_2$ (Zaragoza, 2024). The plan involves employing cutting-edge technologies to analyse, construct, and track carbon sequestration and other ecosystem metrics. This includes the use and analysis of **high-resolution, multispectral satellite imagery** to serve as a basis for analytical work. Additionally, the initiative considers the immediate application of **precision satellite technology** for the automated cataloguing of species and features related to green zones. The project will also develop **land observation indices**, in line with the European USAGE project – Urban Data Space for Green Deal, to assess vegetation health within the city and identify and characterise urban heat islands, which will be marked as priority areas for action. These indices comprise a total of 26 ecosystemic indicators represented in 150x150 m grids and accompanied by a graphic representation by neighbourhood, in what are called "ecosystemic wheels". By doing so, the Council can strategically plan the expansion of its green areas to sequester 5 to 7% of Zaragoza's total carbon emissions.

Helsingborg's monitoring protocol is designed to track the effectiveness of its carbon sequestration efforts and identify areas for improvement (Helsingborg, 2025). The city is using a range of **Key Performance Indicators (KPIs)**, including carbon capture and storage at the district heating plant, changed agricultural practices on agricultural land, and the amount of permanent sequestration of GHG within the city boundary. The city is also monitoring the operation of its new biochar plant, the creation of new parks and green areas, and the restoration of natural land.

Similarly, Leuven monitors the net increase in the number of trees, "neighborhood forests" and green walls, the surface area of agricultural land where carbon sequestration measures have been implemented, the percentage of buildings where the 3-30-300 rule is met, and the structural connectivity and accessibility of green spaces (Leuven, 2024). The city further utilizes a **digital twin** and **citizen science** projects to improve its MRV apparatus.

The City of Mannheim is creating an "**unsealing register**" to keep track of the level of permeability associated with land use, coupled with a **tree cadastre** (Mannheim, 2024). These measures would facilitate integrated urban planning and reduced uncertainty in estimations. The overall intention is to implement the concept of the “sponge city” in a sustainable way, with positive repercussions in terms of carbon sequestration and beyond. Green areas and the unsealing of sealed areas of settlement and traffic areas contribute to reducing the burden of high temperatures during the day and at night in the city. In addition, the unsealing of large areas contributes to improving or restoring the buffer function of the soil during normal as well as extreme rainfall events.

Lahti's MRV system is noteworthy for its transparency, **using net-carbon sink calculation models** and a **carbon map** to track progress (Lahti, 2024). The city is also developing a **local compensation model** and is participating in various projects and initiatives to gather knowledge and expertise.

Greater Dunkirk's monitoring protocol is designed to track the effectiveness of its carbon sequestration efforts and identify areas for improvement (Dunkirk, 2025). The city is using a range of **KPIs**, including the number of species present on site, area of preserved natural areas, and a biodiversity index. Additionally, Dunkirk is tracking the share of organic farming, agro-ecological practices, and certified forest area, as well as the number of trees planted and forest sequestration. The monitoring protocol also includes the use of **GIS visualisation** to spatially represent environmental data and identify areas for improvement.

Trikala's approach to natural carbon sinks emphasises the importance of monitoring and governance around natural carbon sinks (Trikala, 2024). Strategically placed **small measuring stations** will record the rate, degree, and manner of influencing urban green spaces, while **IoT sensors and remotely controlled electrovalves** will enable autonomous energy systems for irrigation, guaranteeing that natural ecosystems can stay healthy and sequester as much carbon as possible.

Trondheim’s and Stavanger’s MRV system involves the **mapping of land use**, assessment of **carbon stores**, and identification of areas with potential for nature restoration (Stavanger, 2025; Trondheim, 2025). A **database** is being developed to map **carbon-rich nature areas**, with a focus on peatlands, forests, and marine sediments. **KPIs** such as natural carbon stocks are used to track progress.

Rzeszow is using **analytical tools**, such as the Obliview platform, to support spatial planning and decision-making and is conducting a comprehensive **inventory of natural resources**, including **canopy maps, tree species and condition, and orthophotomaps** (Rzeszow, 2025). Notably, the Interactive Tree Canopy Map will provide valuable insights into the development of urban greenery.

Finally, Zagreb is tracking green belts, agroforestry zones, and peri-urban corridors as verified carbon sinks (Zagreb, 2025). The city proposes annual **residual emissions inventories by sector**, **MRV protocols for removals**, and public transparency, with residuals and removals tracked on a **public dashboard** alongside emissions reductions. The city also monitors the area of new green spaces, the number of new trees

planted, the number of new shrubs planted, new natural retention areas established, and rain gardens implemented.

## 7.4 Scope 3 emissions

Carbon removals can live at the intersection of multiple urban systems and often produce effects across geographic boundaries. Further, compensation strategies are associated with upstream and downstream emissions components which may transcend the target boundary and that need to be considered in the design of globally effective climate-neutral plans (**Box 42**).

It is common that entities at different sides of the value chain see different impacts in GHG accounting associated with the same activity. A typical case is that the city where the harvesting takes place may see a net loss of biomass (i.e., an emission), whereas the city that is burning biomass to produce energy may see a net GHG benefit from using that biomass. Ultimately, out-of-boundary emissions that occur as a consequence of the city activities (scope 3 emissions) should also be addressed, as cities often have a much larger footprint on land beyond emissions and removals occurring within their boundaries (WRI et al., 2022). Cities may estimate the embodied emissions associated with the production, processing, and transportation of commodities that contribute to deforestation and forest degradation through tools such as the Forest Footprint for Cities tool developed under WRI's Cities4Forests initiative (Cities4Forests, n.d.). Alternatively, corporate or city-specific scope 3 accounting methods could be adapted. This would be critical to ensure leakages and trade-offs are avoided or minimised. Further, considering scope 3 emissions (in decision-making, if not in accounting), may also unveil a wider spectrum of opportunities for limiting residual emissions. For instance, when lifestyle changes remove the need for certain transport or industrial activities, whose decarbonisation challenges would endorse compensation, carbon removal infrastructure can be downsized (and associated risks can be significantly mitigated). A comprehensive approach including emission scopes 1, 2 and 3 could also deliver ecological, safety, and ethical co-benefits. Finally, promoting carbon removals in the built environment can have significant repercussions along construction value chains. If carbon storage is explicitly valued, project developers and public procurers may favour materials that store carbon and, at the same time, have lower lifecycle emissions, such as bio-based or reused materials. Accounting for potential benefits of carbon removals in construction can motivate the use of more sustainable materials and reshape upstream production patterns, supply chains, and trade flows. As a result, emissions that occur outside city boundaries but are embodied in construction materials may decrease (or increase), shift geographically, or change sectorally.

While providing guidance on scope 3 emissions falls out of the scope of this document, another dedicated JRC report ("Tackling out-of-boundary emissions in climate change mitigation at the city level") provides a state-of-art review on current practices in GHG accounting and action in the EU, and on available methods and data to support the development of more comprehensive inventories, including scope 3 emissions (Bastos et al., 2026).

**Box 42**. Scope 3 emissions: mind leakage and double counting

Leakage occurs if mitigation actions to reduce emissions within the target boundary cause increases in emissions from sources, sectors, or gases outside that boundary. Including scope 3 emissions in the target boundary is a very efficient way of identifying and reducing leakage. However, a double counting risk exists since one jurisdiction's out-of-jurisdiction emissions are another jurisdiction's in-jurisdiction emissions. Transparent reporting can help highlight any target overlap resulting from the inclusion of scope 3 emissions. In case emissions reductions and/or removals are to be aggregated across jurisdictions, only the

in-jurisdiction share should be included, as aggregating out-of-boundary emissions may result in double counting.

# 8 Summary of key emissions reporting requirements

Reporting net emissions is key to track progress and determine the achievement of the climate neutrality target. It is acknowledged that limitations currently exist to international reporting as separate presentation of positive, negative, and net emissions along with sold and retired credits is a rather uncommon option.

Nevertheless, emissions reporting should be accurate, complete, consistent, publicly accessible, comparable and transparent. Notably:

- Cities should report emissions in tonnes of carbon dioxide equivalent ($CO_2$-eq), clearly specifying which GHGs are included in the equivalence, which activity data are used, and which emissions and removal factors are adopted.
- Emissions and removals should be reported separately for each relevant sector, subsector, category, activity, carbon reservoir, and gas as relevant. Emissions should be denoted by a positive sign (+) and negative emissions should be denoted by a negative sign (-). In case of very detailed emissions, cities may also explore displaying results in a graphical format. This would be particularly helpful for showing the opposing emissions and removals across sectors and sub-sectors (e.g., via waterfall charts).
- Sold and retired carbon credits should be traceable and transparently reported, i.e., it should be possible to determine their distinct contribution to positive and negative emissions respectively. Cities are encouraged to attach documentation of all credits relevant to local emissions accounting.
- Cities should report their emissions based on the corrected target boundary, i.e., accounting for emissions and removals of any sector, subsector, category, activity, or carbon reservoir included in the target boundary and/or in the residual emissions strategy.
- Exclusions, if any, should be clearly declared (i.e., no ambiguity should exist within and across sectors on what is accounted for) along with a compelling justification.
- Cities should describe all calculation methods adopted and any use of special accounting provisions, such as those associated with natural disturbances. If any sector, subsector, category, activity, or carbon reservoir is treated with a different approach, the rationale for this choice, the new accounting methodology, and the potential impacts should be disclosed. A qualitative if not quantitative assessment of the overall uncertainty is desirable.

Consistency across inventory cycles is necessary for calculating trends over time. Thus, baseline and subsequent inventories should share the same methodological framework (incl. type/source of data, assumptions, definitions, accounting methods). For instance, where the land sector is concerned, it is critical that the same land use definitions are applied consistently throughout the inventory so that changes in definitions do not appear in the inventory as land use changes (WRI et al., 2022). This means that if changes are applied to calculate the emissions for a new inventory, previous inventories shall be retroactively updated using the same methods. In general, the following issues could trigger a methodological adjustment: changes in reporting methodologies, new data or corrections of statistical errors, inclusion of new carbon reservoirs or gases, recalculation of historical estimates based on new scientific evidence, inclusion of new reporting elements and improved monitoring of natural disturbances if relevant (European Parliament and Council, 2023b).

Accounting for negative emissions is particularly prone to recalculation as existing methodologies are still evolving, new methodologies are being developed for uncovered sub-sectors, technological advancements are accelerating, and datasets based on satellite imagery are increasingly becoming popular and gaining accuracy. Where previous inventories cannot be recalculated with more recent data, cities should attempt to establish a relationship between the new and old data sources and then backcast the new data (WRI et al., 2022). Comparability across time should be discussed and sources of uncertainty should be transparently raised.

# 9 EU policy context

Under the current framework, the most relevant legislation concerning carbon removals is the Carbon Removal and Carbon Farming Regulation (CRCF) (European Parliament and Council, 2024b), establishing the first EU-wide framework to certify high-quality carbon removals and soil emission reductions. This Regulation entered into force in December 2024, and lays the foundation for the transparent, science-based certification of carbon removal activities across the Union.

The aim of this Regulation is to facilitate and encourage the deployment of permanent carbon removals, temporary carbon removals from carbon farming, temporary carbon storage in products, and soil emission reductions. This framework is intended to facilitate and encourage the uptake of high-quality carbon removals and soil emission reductions, while fully respecting the Union's biodiversity and zero-pollution objectives, serving as a complement to sustained emission reductions across all sectors.

The CRCF covers the certification of:

— Permanent carbon removals, such as direct air capture with geological storage or biochar carbon removal.

— Carbon farming, including temporary carbon storage in soils and biomass and soil emission reductions.

— Carbon storage in long-lasting products, such as temporary carbon storage in bio-based buildings.

Soil emission reductions and temporary removals via carbon farming are included, provided they are quantified with high accuracy, typically using Tier 3 IPCC methodologies, and meet minimum sustainability and duration thresholds.

To ensure integrity, the CRCF applies the **QU.A.L.ITY criteria** to all certified activities (as demonstrated in **Section 7.2.1** for the built environment):

— **Quantification**. Removals shall be measured precisely and conservatively.

— **Additionality**. Only activities that go beyond business-as-usual are eligible.

— **Long-term storage**. Permanence shall be demonstrated and reversal risks addressed.

— **Sustainability**. Removals shall respect environmental and social safeguards, including biodiversity protection, soil health, and pollution prevention.

The CRCF's QU.A.L.ITY criteria are fully aligned with the guiding principles outlined in **Section 6** of this guidance, and thus with the Cities Mission.

Carbon farming activities shall have a minimum activity duration of 5 years, generate net removals or emission reductions, deliver co-benefits for ecosystems and avoid land degradation. Carbon storage in products shall be monitored for at least 35 years; if no extension is committed beyond this period, the stored carbon is considered re-emitted.

The certification process is designed to ensure the credibility and reliability of certified carbon removals and soil emission reductions through independent third-party auditing. The certification is carried out by independent certification bodies, accredited or recognised by national authorities, and proceeds in the following stages. In an initial certification audit (ex ante) the project design is

verified against QU.A.L.ITY criteria. If compliant, a certificate of compliance is issued. The post-implementation audit (ex post) confirms that removals have been delivered as planned. If verified, certified carbon removal units are issued and recorded in a public EU registry. Periodic re-certification audits are conducted at least every 5 years (or more frequently, depending on the project type) to maintain the validity of the certificate and ensure ongoing compliance. All certified units will be issued and tracked via a centralised, interoperable EU registry, ensuring transparency and traceability. The Commission shall establish by 27 December 2028 and maintain a Union registry for this purpose. Until then, individual certification schemes shall establish and maintain their own interoperable certification registries.

The Regulation is supplemented with an implementing act detailing operation, recognition and assessment rules for certification schemes and registries (available by 2026). Delegated acts establish detailed certification methodologies tailored to each type of carbon removal activity. By 2026, the following certification methodologies should become available (European Commission, 2026): direct air capture with carbon storage, biogenic emission capture with carbon storage, biochar with carbon removal, agriculture and agroforestry on mineral soils, peatland rewetting and restoration, planting of trees and carbon storage in buildings.

Certified removals under the CRCF contribute to the EU's Nationally Determined Contribution (NDC). To avoid double counting, certified removals cannot be claimed under third-country NDCs or international compliance schemes.

The Regulation builds on and connects with the following existing experience at EU level:

- **The Innovation Fund** (European Commission, 2025), under which the Commission has developed a number of EU methodologies for the quantification of GHG emission avoidance of industrial activities, including carbon removals from BioCCS and DACCS projects. The Innovation Fund is financed by the revenues from the EU Emissions Trading System (EU ETS) (European Parliament and Council, 2003), thereby helping businesses invest in innovative clean technologies, including those generating permanent carbon removals. In 2023, the revision of the EU ETS Directive strengthened the Innovation Fund as follows: the overall size of the Innovation Fund has been increased from 450 million ETS allowances to approximately 530 million ETS allowances (European Commission, 2023b).
- **The CCS Directive** (European Parliament and Council, 2009), establishes a legal framework for the safe selection of storage sites and regulates the concession of storage permits. Moreover, it includes provisions on $CO_2$ capture and transport, further developed in the Industrial Emissions Directive 2010/75/EU. The CCS Directive is particularly relevant for BioCCS and DACCS. Monitoring rules and liability mechanisms for permanent carbon removals are consistent with this Directive. Bioenergy production is primarily regulated in the Renewable Energy Directive (RED, see below). However, the legal framework affecting biomass goes beyond energy regulation and includes other policy areas such as environment, climate and agriculture.

— **The LULUCF Regulation** (European Parliament and Council, 2018) and its 2023 Amendment (European Parliament and Council, 2023b) is an instrument for enhancing carbon removals in terrestrial ecosystems. It sets out rules around i) the commitments of Member States for the land use, land use change and forestry ('LULUCF') sector concerning GHG emissions and removals; ii) the accounting of GHG emissions and removals from the LULUCF sector; iii) a 2030 Union target for net GHG removals (i.e., removals minus emissions) in the LULUCF sector set at 310 millions $tCO_2$-eq by 2030; and iv) targets for net GHG removals in the LULUCF sector for each Member State for the period from 2026 to 2030 taking into account the Member State's baseline emissions in the sector, managed land share, and capacity to improve the sector's performance. Each Member State is called on ensuring that GHG emissions do not exceed GHG removals, calculated as the sum of total emissions and total removals on its territory in all of the following land use reporting categories or sectors: forest land, cropland, grassland, wetlands, settlements, other land, harvested wood products, atmospheric deposition, nitrogen leaching, and run-off. The CRCF draws on the definition of biogenic carbon pools and requires compatibility with national greenhouse gas inventories under this Regulation. More details on the accounting scope of the Regulation are provided in **Table 12**.

— **The EU Renewable Energy Directive (RED)** 2023 revision, known as RED III (European Parliament and Council, 2023a), through which the Commission has gained nearly 15 years of experience in the certification of sustainability criteria for bioenergy. Under RED, the Commission has recently adopted an implementing act setting detailed rules for the certification process carried out by certification bodies and controlled by certification schemes. The core of the Directive is to increase the share of renewable energy in the EU's gross energy consumption to 42.5% by 2030, with an indicative target of an additional 2.5%, all the while enforcing stricter rules on alternative fuels (hydrogen, biofuels, and biomass). The sustainability and greenhouse gas emissions saving criteria for biofuels, bioliquids, and biomass fuels established under this Directive are critical for CRCF activities involving biogenic $CO_2$. The principle of the cascading use of biomass, as laid down in Article 3(3) of this Directive, is also applied.

— The revised **Energy Performance of Buildings Directive** (European Parliament and Council, 2024c)**.** This Directive introduces requirements for lifecycle carbon assessment of buildings and addresses carbon removals. There are strong synergies envisioned between EPBD and CRCF methodologies, especially for developing standardised baselines and monitoring. Article 7 requires Member States to address various aspects of new buildings, including the role of carbon removals through carbon storage in or on buildings. Additionally, Annex II sets out the template for national building renovation plans, as referenced in Article 3, requiring Member States to outline implemented and planned policies and measures - such as the reduction of whole life-cycle greenhouse gas emissions across construction, renovation, operation, and end-of-life stages, along with the integration of carbon removals. Furthermore, Annex V, which provides the template for energy performance certificates (as per Article 16), may also include information on carbon removals linked to temporary carbon storage in or on buildings. With the revised EPBD allowing building owners to declare the carbon storage capacity of their structures on their Energy Performance Certificate (EPC), reliable evidence can be gathered through the CRCF certification methodology for carbon storage in products. This enables buildings' carbon storage capacity to be demonstrated transparently.

— The revised **Construction Products Regulation (CPR)** (European Parliament and Council, 2024a). This Regulation sets harmonised rules for assessing and disclosing the environmental impacts of construction products, including lifecycle data and digital product passports. Future harmonised standards under CPR are expected to supersede interim CRCF's methodologies for product-level data.

— The **Nature Restoration Regulation** (European Parliament and the Council, 2024b) requires Member States to restore ecosystems. The CRCF encourages alignment with the objectives of this regulation by requiring activities, particularly carbon farming, to deliver co-benefits for bio-diversity protection and restoration, and consistency with relevant national restoration plans.

— The **EU Taxonomy Regulation** (European Parliament and Council, 2020) defines criteria for sustainable economic activities, including climate mitigation, adaptation, and "do no significant harm" (DNSH) principles. The CRCF sustainability requirements build up on the criteria set out in Appendix A to Annex 1 of this Delegated Regulation, particularly for DNSH criteria related to climate change mitigation and adaptation.

— The **Corporate Sustainability Reporting Directive (CSRD)** (European Parliament and Council, 2022) mandates companies to report on sustainability impacts. The Commission will assess alignment with this Directive concerning the use of certified units for corporate claims and sustainability reporting.

**Table 12.** LULUCF Regulation: land accounting categories, GHGs, and carbon reservoirs

| | | |
|---|---|---|
| **Land accounting categories** | Forest Land | FL remaining FL ("managed forest land")<br>Cropland, grassland, wetlands, settlements or other land, converted to FL ("afforested land")<br>FL converted to cropland, grassland, wetlands, settlements or other land ("deforested land") |
| | Managed cropland | Cropland remaining cropland<br>Grassland, wetland, settlement or other land, converted to cropland<br>Cropland converted to wetland, settlement or other land |
| | Managed grassland | Grassland remaining grassland<br>Cropland, wetland, settlement or other land, converted to grassland<br>Grassland converted to wetland, settlement or other land |
| | Managed wetland | Wetland remaining wetland<br>Settlement or other land, converted to wetland<br>Wetland converted to settlement or other land |
| **Greenhouse gases** | $CO_2$, $CH_4$, $N_2O$ | |
| **Carbon reservoirs** | Living biomass; litter*, deadwood*, dead organic matter**, mineral soils, organic soils, harvested wood products in the land accounting categories of afforested land and managed FL. | |

*Applies to Afforested Land and Managed Forest Land only
**Applies to Deforested Land, Managed Cropland, Managed Grassland and Managed Wetlands only.

*Source: JRC analysis.*

The CRCF is also strongly interlinked with other Commission initiatives on improving the resilience of the EU's forests to climate change, restoring degraded land and ecosystems, rewetting peatlands and promoting the bio-economy, including the use of durable harvested wood products, in full respect of ecological principles fostering biodiversity:

— The Common Agricultural Policy (European Commission, 2023a)

— EU Biodiversity Strategy for 2030 (European Commission, 2020b)

— Farm to Fork Strategy (European Commission, 2020c)

— EU Forest Strategy (European Commission, 2021d)

— EU Soil Strategy for 2030 (European Commission, 2021e)

— EU Strategy on Adaptation to Climate Change (European Commission, 2021a)

— A sustainable Bioeconomy for Europe (European Commission, 2018a)

— Circular Economy Action Plan (European Commission, 2020a)

— Zero Pollution Action Plan (European Commission, 2021c)

— A long-term Vision for the EU's Rural Areas (European Commission, 2021b).

# 10 Conclusions, recommendations, and outlook

This document provides guidance on how cities should approach negative emissions in view of achieving the climate neutrality target as set out in the framework of the 100 Climate-Neutral and Smart Cities Mission. The principles and processes delineated here are geared towards crafting a robust strategy for residual emissions that aligns with international best practices and supports the legitimacy of cities' journey towards climate neutrality. The guidance is designed for cities selected in the Mission; however, key messages and methodological processes would benefit any city on the journey to net-zero emissions.

The key insights from this guidance can be condensed as follows:

— In net-zero targets, **residual emissions** are those emissions remaining at the closure of the target-year inventory period after all technically and economically feasible opportunities for emissions reduction have been implemented. Residual emissions **shall not be defined through target-setting**, but via a critical analysis of local sources of emissions and associated constraints in abatement, whose severity dictates the necessity to compensate. This **analytical process is iterative**, to respond to technological advancements, market dynamics and situational evolutions. Succeeding in this exercise stimulates ambitious climate action and improves accountability among various government levels and external stakeholders. Failing in this exercise may delay fossil fuels phasedown, increase system-wide spending in the longer run, and create pressure for an oversized carbon removal which in turn might face physical constraints and limited technological readiness.

— To achieve net-zero, **residual emissions shall be compensated** through in-boundary emissions removals and/or purchase of out-of-boundary carbon removal credits.

- **Emissions removals** shall originate from **deliberate anthropogenic activities** that remove GHGs **from the atmosphere** in a **durable** manner in addition to the removal that would occur via natural carbon cycle processes. **Net negative emissions** are achieved when the total quantity of atmospheric GHGs removed and durably stored exceeds the total quantity of GHGs emitted to the atmosphere through the same activities. The origin of the greenhouse gases is atmospheric, either capturing them directly from ambient air or indirectly from biomass. Capture and storage or utilisation from fossil sources do not realise a removal but contribute to lowering the level of residual emissions.

- **Examples of deliberate anthropogenic activities** that generate emissions removals are afforestation and reforestation, forest ecosystem restoration, improved forest management (including agroforestry, silviculture, timber in construction and bio-based products), revegetation, soil carbon sequestration, wetlands restoration and blue carbon management, along with more durable options like biochar, BioCCS, DACCS, enhanced rock weathering, mineral carbonation, ocean alkalinity enhancement and artificial ocean fertilisation. **High storage integrity** options (like BioCCS and DACCS) are typically less vulnerable to **reversal** than carbon sequestered in the soil or vegetation. **Temporary removals** may have large and essential co-benefits; however, climate change itself is destabilising their storage capacity raising questions about relying on them too heavily for net-zero claims. The value proposition of temporary removals strengthens significantly when **complemented with permanent removals**. A **like-for-like counterbalancing** in terms of emissions origin and residence time should be pursued.

- In the Cities Mission, **retired (bought) carbon credits** can be used to compensate for residual emissions **exclusively if** they are attached to **removal** activities (emissions reduction and avoidance credits are excluded), qualify as **high-quality certified units** as defined by the EU Carbon Removal and Carbon Farming Regulation (any abiding certification scheme would be valid), and **do not originate from activities the city has excluded from the target boundary**. These criteria ensure the quantification of a net carbon removal or soil emission reduction benefit in a relevant, conservative, accurate, complete, consistent, transparent, and comparable manner. They also avoid the paradox where cities propose exclusions from the target and then claim carbon credits from activities on those exclusions. The quality of a carbon credit is directly related to the integrity of the activity that underlies the credit. A number of attributes are considered including climate and socio-environmental impacts, additionality, baselines, leakage, and permanence.

- The negative emissions associated with **carbon removal credits sold** to an entity outside the municipality's territory **cannot count** towards its **net-zero** balance.

- Cities can approach carbon credits as project **developers**, **investors** or **buyers**. The choice is city-specific and highly depends on the city capacity to technically and/or economically support carbon credits. Cities taking a developer or investor role in carbon offsetting may be better positioned to ensure greater co-benefits and better alignment with local priorities. Cities can also **individually or collectively** enter into long-term offset purchase agreements, coordinate efforts by creating a shared public procurement mechanism or platform (cooperative purchasing) or encourage sector-specific alliances to leverage shared opportunities.

- Cities involved in the Mission are advised to build a portfolio of credits that **prioritises ex-post carbon credits** (those issued once the carbon benefit has materialised). Ex-ante and pre-purchased credits may be considered notably when dealing with carbon removal projects that are highly innovative and have the potential for large, scalable, and highly durable carbon storage; however, **ex post verification** of the contribution achieved **by target year** is required. This means cities cannot claim removals before they are delivered and verified to avoid the pitfalls of premature crediting.

- Cities should consistently **allocate** carbon credit **revenues towards climate action** initiatives, fostering self-sustained mechanisms that drive increased ambition and progress toward a net-zero future.

— A **city** can support removals within its boundaries and beyond mainly through **technological, regulatory, financial and political-economic levers**. Depending on its specific constraints, a city can use these levers to a greater or smaller extent, placing them in different **roles** in relation to the carbon removal stakeholder ecosystem: **strategiser, regulator, service provider, innovator, funder, convener or a combination of these roles**. Cities should identify their primary role or orientation, as this will shape their overall approach.

— A robust residual emissions strategy follows **six core principles**:

- **Emissions Reduction First Principle**. Emissions compensation is never a substitute for feasible **emissions reductions**, which always remain the **priority**. No-regret removal strategies may be pursued in parallel for their **additional benefits**, but shall never deter, delay, or sidetrack emissions reduction efforts. This also guarantees that where residual emissions exist, compensation mechanisms do not trigger side effects that would adversely alter the net impact on emissions. Removal methods can deal with sources of anthropogenic emissions as well as legacy emissions already accumulated in the atmosphere and troposphere, against which emissions reduction today has no effect. **Separate targets** for emissions reduction and compensation, adequate **regulation** of the use cases of CDR, along with **oversight transparency** and **quality assurance**, can neutralise the moral hazard of carbon removal delaying emissions reductions.

- **Transparency Principle**. Cities shall **report accurately** and **transparently** the gases, sectors, and subsectors (and the applicable definitions) included in the **target boundary** and disclose any **exclusions**. No ambiguity should exist on the accounting coverage and on its overlap with the target boundary. Further, cities shall report **separately** all **positive** (i.e., emissions and sold credits), **negative** (i.e., removals and retired credits) and **net emissions** (positive minus negative emissions), in a manner that **prevents** any possibility of **double counting**. When a sector or sub-sector is included in either the target boundary or in the residual emissions strategy, all accountable emissions (and removals) shall be transparently included (**no selective approach**). Therefore, cities shall not leverage the AFOLU sector for its potential negative emissions, without accounting for the associated positive emissions. **Carbon credits** shall always be **issued in a publicly available registry** to ensure transparency, traceability, and accountability with measures in place to prevent double counting, double selling, or double claiming. Cities should provide full access to sufficient **information** to rebuild the **methodological steps** used for accounting, monitoring, reporting, and verification (from the selection of emission factors to the treatment of natural disturbances). Finally, cities should **disclose publicly** their compensation strategy to ensure community buy-in and increase the social licence of CDR through **symmetrical and accurate communication**. These aspects should be discussed in the action plan together with measures to ensure good governance, transparency, and accountability for negative emissions.

- **Environmental and Ethical Integrity Principle**. Removals and credits should be leveraged to deliver net-zero targets with careful **consideration** of potential unintended **negative impacts and impermanence**, based on the best available information and research advancements at the time of planning (and/or implementation). These include **undesired environmental effects** (on e.g., air quality, biodiversity, energy, food and yield, land use, water security) and negative implications on **social and climate justice** (e.g., green gentrification, food insecurity, job loss, hunger, poverty and regressive welfare loss). Cities should pursue a **fair distribution of risks and benefits** and design credible **remediation plans** and **buffers** against potential threats to the environmental and ethical integrity of their residual emissions strategy. As those tend to intensify with the scale of implementation, large-scale CDR should be carefully conceived, tested and monitored.

- **Co-benefits Principle**. Cities should **prioritise** removal technologies, techniques, and credit-generating projects that maximise the **co-benefits** in the local territory (and beyond) and the **synergies** with other city goals and action plans. Co-benefits include climate change mitigation and adaptation, the protection and restoration of biodiversity and ecosystems, the sustainable use and protection of water and marine resources, the transition to a circular economy, and pollution prevention and control. In the context of carbon credits, co-benefits might **increase the value** and potential market premium of the certified carbon removals, depending on the certification framework. Compensation strategies attentive to co-benefits promote integrated urban planning, multilevel governance, sector coupling, and investors' buy-in.

- **Diversification Principle**. Cities should pursue diversified strategies across different solutions, projects, geographies, and standards to i) **overcome** the **limitations** and potential failure of individual practices, ii) **distribute risks**, iii) achieve **multiple objectives**, iv) better handle **permanence**, v) hedge against **market fluctuations, regulatory changes, and potential supply shortages**, and iv) make offsetting **stable and affordable** to more comfortably venture in ambitious projects.

- **Cost and Time Effectiveness Principle**. Cities should **examine** for each compensation option: supply and demand, price volatility, project and technology costs, potential implementation sites and local standards, co-benefits and potential adverse impacts, project size, contracting and stakeholder arrangements, etc. **Early adoption** favours on-time appreciation of effects, resource availability, reduced cost and regulatory uncertainties, and additional time for project development or remedial action to fulfil the climate neutrality ambition. **Late adoption** favours greater technological and market maturity, more time for peer-learning opportunities, stakeholder coordination, and feasibility studies/pilot tests while reducing the risk of over-reliance on compensation and accusations of greenwashing.

— Concerning the **land sector** (e.g., forests, trees, wetlands), cities should take into account the **dual role** of these ecosystems as both GHG sources and sinks. Cities may choose between **land-based and activity-based accounting approaches**, but shall ensure that their accounting method is transparent, consistent, and compliant with IPCC guidelines. Cities should quantify emissions and removals associated with **land use changes**, **forest disturbances**, and other activities, and may use default **emission factors** and **carbon gain factors** where local data is unavailable. Cities are expected to prioritise the **health** and resilience of urban trees and forests, avoid monocultures and exotic species, and may consider introducing drought-resistant species, and select species with low emissions of volatile organic compounds.

— Concerning **carbon storage in buildings**, cities should follow fundamental GHG accounting principles, such as consistency, transparency, accuracy, completeness, and comparability. Cities may use the CRCF methodology and shall ensure that their accounting system is compliant with EU regulations and guidelines. Cities may use **default and standardised coefficients** to estimate carbon storage. They shall also consider the permanence of carbon storage, and may use **duration thresholds, reversal adjustments, and design end-of-life practices** to ensure that carbon is stored for a minimum period. Cities may use recognised **certification systems**, such as FSC and PEFC, to ensure that materials are sourced sustainably and may implement **material passports**, **digital building logbooks**, and **urban material registries**, to track and report carbon storage in buildings.

— **Monitoring Reporting and Verification provisions shall be in place** for any carbon removals and for the entirety of their expected lifetime. Establishing a baseline inventory and producing monitoring inventories for the AFOLU sector and any activity cities intend to leverage to produce negative emissions may constitute a data-intensive and uncertainty-affected step in the accounting process. Complexity and feasibility vary with removal method and data accessibility. Cities should **manage uncertainties** through advanced digital technologies and robust data management practices. Accurate carbon accounting and MRV frameworks for forest and urban land enable a responsible large-scale adoption of biomass-based solutions against land availability and competition.

In addition, cities on a genuine and effective climate-neutrality pathway:

— Should make sure that the selected target boundary and accounting method would make it possible to include and appreciate the effects of their residual emissions strategy. Cities are encouraged to carefully assess which sector(s), gas(es), and geographical area(s) would be impacted by the strategy and adjust the political commitment to their factual commitment. This should be reflected in how emissions are calculated and reported, to ensure that the emissions inventory is responsive to the effects of the strategy. In the event that the city is implementing GGRs not in their climate mitigation, but in their climate adaptation strategy[19], it is recommended to treasure consistency in view of building synergies and avoiding or mitigating trade-offs between the two climate goals.

[19] This is particularly relevant for cities engaged in both the Cities Mission and in the Mission on Adaptation to Climate Change.

— Shall claim emissions reductions and removals when no double counting risk exists. This includes setting up agreements with other parties. This is typically the case of biomass-related strategies (e.g., BioCCS, timber in construction) where biomass is imported. In these cases the CDR activity could be reported either at the time the carbon was transferred from atmosphere to the biomass or in the year of biomass conversion to an energy product or wood product. While the time misalignment might be negligible (when using annual crops, but not forest biomass and other perennial crops), these volumes run the risk of being double counted if CDR methods make use of biomass that has also been recorded as a sink in prior years. A recommended approach to avoid double counting is to record the carbon removed from the atmosphere always in the year in which it actually occurs (this will be reflected in the inventory), and record separately activities such as the production of durable harvested wood products or energy as carbon transfers in the year of production (S. M. Smith et al., 2023). This ensures tracking of both flows, while not incurring accounting issues.

— Should support the setup of dedicated monitoring networks, managed by the city, local universities, non-governmental organisations, and/or other private or public stakeholders at different governance tiers. By investing today in monitoring, data collection, and data storage, cities would ensure a gradual refinement of emissions inventories and a stronger evidence for taking action and sizing carbon removals. Changes would be retroactively applied to previous inventories and the inventories recalculated, including the baseline inventory. This would guarantee more robust plans and policies (reduced risk of failures), and an accounting process more responsive to local specificities.

— May provide for advisory services, technical advice, training, and financial support to land managers, especially small farmers and forest holders. These efforts will enhance their capacity to implement carbon removal activities and comply with the requisite quality criteria. The Common Agricultural Policy and national State aid can support financially the provision of advisory services, knowledge exchange, training, information actions or interactive innovation projects with farmers and foresters.

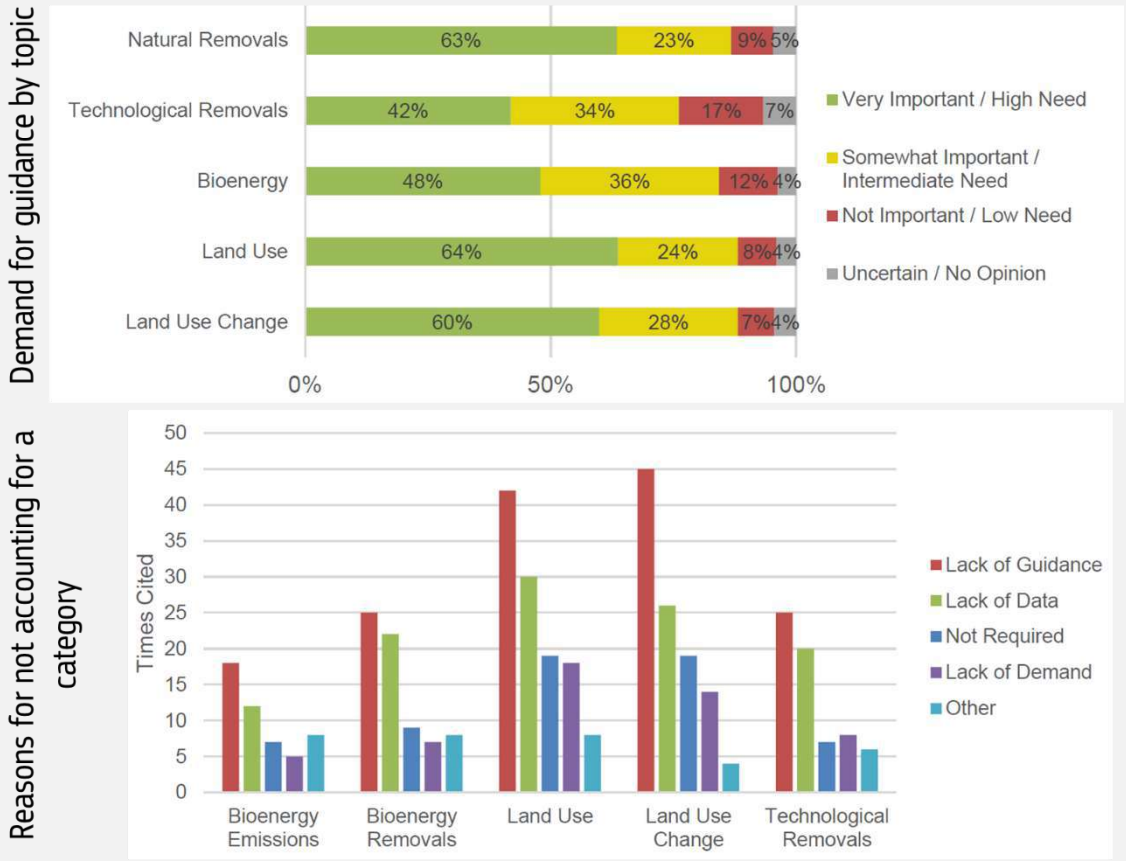
This guidance serves as a foundation for cities to develop and refine their strategies for achieving climate neutrality, providing a clear pathway for incorporating negative emissions into their climate action plans. Common principles on emissions reporting and emission compensation mechanisms are enlisted and defined. As the regulatory, methodological, and scientific landscape surrounding negative emissions continues to evolve, it is anticipated that additional rules and guidance will emerge to further refine these processes (**Box 43**). Further, the upcoming IPCC Methodology Report on Carbon Dioxide Removal Technologies, Carbon Capture, Utilization, and Storage for National Greenhouse Gas Inventories (Additional guidance) and IPCC Special Report on Climate Change and Cities (publication foreseen in 2027) might contribute to the overall scientific foundation around CDR methods used in urban settings.

Pioneering cities within the Mission will play a pivotal role in the development and deployment of carbon dioxide removal (CDR) methods, contributing to a broader understanding and application of these strategies. The outlook for CDR methods is promising. With appropriate market signals and demand creation, CDR technologies could experience steep advancements, bolstered by political commitment and strategic investments. The future of carbon pricing and incentives will also be instrumental in making GGR methods economically viable and driving their large-scale adoption.

**Box 43.** What is cooking?

An online survey distributed by WRI in 2019 and answered by 417 individuals (from businesses, governments, NGOs, academic/research institutions and consultants) across over 50 countries, investigated where more guidance is most hoped for in the domain of carbon removals (GHG Protocol et al., 2023). The results (showed in **Figure 8**) demonstrate a widespread consensus (76%-88%) that new guidance is either very important or somewhat important, notably in relation to the land sector. Future efforts will thus aim to address this need, as detailed in (GHG Protocol et al., 2023). Moreover, **Figure 8** illustrates that although the absence of guidance ranks as the primary reason for not accounting for emissions and removals linked with the land sector, bioenergy, and technological removals, the scarcity of data consistently holds the second position. Streamlining the data-intensive process that is behind the accounting of negative emissions would help crafting accounting methodologies that better respond to the resources and constraints of local governments. Whether in the form of simplified methods, locally-adapted methods, or multi-level methods (with different governance tiers involved), this is a critical gap to materialise urban net-zero targets.

**Figure 8.** Key results of WRI's survey on pressing needs for carbon removal accounting and removal.




*Source: (GHG Protocol et al., 2023)*

In terms of upcoming guidance, the delegated acts that will accompany the EU Carbon Removal and Carbon Farming Regulation with certification methodologies may offer valid approaches for Mission Cities. Given the need to rapidly scale up carbon removals in the Union, the Commission might prioritise methodological input for the following activities: activities that are the most mature, that can provide sustainability co-benefits or where Union legislation relevant for the development of those methodologies has already been adopted; carbon farming activities that contribute to sustainable management of agricultural land, forests, and the marine environment as well as activities that store carbon in wood-based and bio-based construction products.

In parallel, DG CLIMA is investigating how to generate the demand for large-scale deployment of CDR technologies. Three reports have been published in August 2025 in collaboration with Ecologic Institute and Ramboll Management Consulting to fully map the investment pathway for permanent CDR, from current estimated prizes and barriers (European Commission & Ramboll Management Consulting, 2025a), to existing and innovative financing tools (European Commission & Ramboll Management Consulting, 2025b), and short-term policy design (European Commission & Ecologic Institute, 2025), as discussed also in **Box 14**. The ultimate aim is to explore the design of an EU-wide purchasing programme for permanent CDR to encourage investment, boost technological progress and help meet EU climate targets. The reports closely look at 2030 and 2035 as timelines, which strongly aligns with the Cities Mission own pathway.

## References


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## List of abbreviations and definitions

| Abbreviations | Definitions |
|---|---|
| AFOLU | Agriculture, Forestry, and Other Land Use |
| AGP | Active Growing Period |
| AMR | Atmospheric Methane Removal |
| AOF | Artificial Ocean Fertilisation |
| AR | Afforestion and Reforestation |
| BAT | Best Available Technique |
| BAU | Business-As-Usual |
| BECCS/BioCCS | Bio Energy with Carbon Capture and Storage |
| BVOC | Biogenic Volatile Organic Compound |
| CA | Corresponding Adjustment |
| CaO | Lime |
| CAP | Common Agricultural Policy |
| CC | Carbon Credit |
| $CC_{retired}$ | Carbon Credit (Retired) |
| $CC_{sold}$ | Carbon Credit (Sold) |
| CCC | Climate City Contract |
| CCP | Core Carbon Principle |
| CCS | Carbon Capture and Storage |
| CCUS | Carbon Capture with Utilization or Storage |
| CDM | Clean Development Mechanism |
| CDR | Carbon Dioxide Removal |

| Abbreviations | Definitions |
|---|---|
| $CH_4$ | Methane |
| CNAP | Climate Neutrality Action Plan |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| $CO_2$-eq | Carbon Dioxide Equivalent |
| $CO_{2FL \rightarrow NFL}$ | Emissions from Forest Land converted to Non Forest Land |
| $CO_{2FL,dist}$ | Emissions associated with Disturbance on Forest Land remaining Forest Land |
| $CO_{2FL,undist}$ | Removals associated with Undisturbed conditions on Forest Land remaining Forest Land |
| $CO_{2net, F \& T}$ | Net Emissions from Forests and Trees |
| $CO_{2NFL \rightarrow FL}$ | Removals from Non Forest Land converted to Forest Land |
| $CO_{2NFL,gain}$ | Removals from Gained and maintained trees on Non Forest Land |
| $CO_{2NFL,loss}$ | Emissions from Loss of trees on Non Forest Land |
| CORSIA | Carbon Offsetting and Reduction Scheme for International Aviation |
| CPR | Construction Products Regulation |
| CRCF | Carbon Removal and Carbon Farming Regulation |
| DACCS | Direct Air Carbon Capture and Storage |
| DG | Directorate General |
| DNSH | Do No Significant Harm |
| EC | European Commission |

| Abbreviations | Definitions |
|---|---|
| EPBD | Energy Performance of Buildings Directive |
| ERW | Enhanced Rock Weathering |
| ESR | Effort Sharing Regulation |
| ETS | Emissions Trading System |
| EU | European Union |
| EW | Enhanced Weathering |
| FL | Forest Land |
| GGR | Greenhouse Gas Removal |
| GHG | Greenhouse Gas |
| $GHG^{+}$ | GreenHouse Gas Emissions |
| $GHG^{-}$ | GreenHouse Gas Removals |
| $GHG_{net}$ | Net GreenHouse Gas Emissions |
| GIS | Geographic Information System |
| GPC | Global Protocol for Community-Scale Greenhouse Gas Emission Inventories |
| $GtCO_2$ | One Billion Tonnes of Carbon Dioxide |
| GWP | Global Warming Potential |
| ICT | Information and Communication Technology |
| ICVCM | Integrity Council for the Voluntary Carbon Market |
| IFM | Improved Forest Management |
| IPCC | Intergovernmental Panel for Climate Change |
| IPPU | Industrial Processes and Product Use |

| Abbreviations | Definitions |
|---|---|
| ITMO | Internationally Transferred Mitigation Outcomes |
| IWMS | Inland Wetland Mineral Soils |
| JI | Joint Implementation |
| JRC | Joint Research Centre |
| $kgCO_2$ | One Kilogram of Carbon Dioxide |
| KOH | Potassium hydroxide |
| KPI | Key Performance Indicator |
| LCA | Lifecycle Assessment |
| LUCAS | Land Use/Cover Area frame Survey |
| LULUCF | Land Use, Land Use Change and Forestry |
| MEA | Monoethanolamine |
| MRV | Monitoring, Reporting and Verification |
| MSW | Municipal Solid Waste |
| $MtCO_2$ | Million Tonnes of Carbon Dioxide |
| $N_2O$ | Nitrous Oxide |
| N&P | Nitrogen and phosphorus |
| NaOH | Sodium Hydroxide |
| NBS | Nature Based Solutions |
| NDC | Nationally Determined Contribution |
| NFL | Non Forest Land |
| NSCA | North Sea Canal Area |

| Abbreviations | Definitions |
|---|---|
| OAE | Ocean Alkalinity Enhancement |
| OIMP | Other International Mitigation Purposes |
| PACM | Paris Agreement Crediting Mechanism |
| PAN | PeroxyAcetyl Nitrate |
| PM | Particulate Matter |
| REC | Renewable Energy Credit |
| RED | Renewable Energy Directive |
| RES | Renewable Energy Source |
| SCS | Soil Carbon Sequestration |
| SDG | Sustainable Development Goal |
| SOA | Secondary Organic Aerosols |
| $tCO_2$-eq | Tonnes of Carbon Dioxide Equivalent |
| $tCO_2$/yr | Tonnes of Carbon Dioxide per Year |
| TRL | Technology Readiness Level |
| UNFCCC | United Nations Framework Convention on Climate Change |
| VCM | Voluntary Carbon Market |
| VCS | Verified Carbon Standard |
| WAE | Wastewater Alkalinity Enhancement |
| WMO | World Meteorological Organization |
| WRI | World Resource Institute |
| WWTP | Wastewater Treatment Plant |

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## Annexes

In the **Annexes**, the main removal methods are described and grouped under temporary CDR methods (**Annex 1**), permanent CDR methods (**Annex 2**), and removal options for other GHGs (**Annex 3**). The **Annexes** serve as entry points to quickly grasp the variety of strategies and implementation options, their physical mechanisms and scientific basis, their characteristics, maturity and most relevant impacts. The **Annexes** condense information relevant to decision-making; however, for a deeper understanding of each option, the reader can consult IPCC resources (e.g., (IPCC Working Group III, 2022a)) and dedicated documents, some of which are listed below:

- In (European Commission & Ramboll Management Consulting, 2025a), the authors propose a summary of the current state and future potential of permanent CDR (see **Annex 2**) in Europe. More specifically, the report assesses removal potential (future supply), costs, funding needs and opportunities, and current deployment and scale-up barriers. It analyses and maps existing and planned carbon removal projects across the EU, with a focus on understanding the region's current capabilities and future needs. The document emphasises ongoing and planned projects in Europe in 2030 and 2035 with a specific interest in expected investments, financing needs and funding available.
- In (S. M. Smith et al., 2023), the authors produce the first State of Carbon Dioxide Removal report, covering a variety of aspects on the state of play of CDR, from research to policymaking and deployment, from scientific analysis to public perception. The report is not intended as a one-off exercise and is updated regularly to inform policymakers on the state of progress, by systematically collecting and analysing vast amount of data and developments in many parts of the world. The 2$^{nd}$ and latest edition dates back to June 2024 (S. M. Smith et al., 2024). The 3rd edition is planned for May 2026.
- In (The Royal Society, 2018), cities can find a systematic description of different solutions, including i) basic principles of operation, ii) storage potential and longevity of storage, iii) natural resources required, iv) environmental benefits and challenges, v) scalability and engineering challenges, vi) risks to implementation, vii) monitoring and evaluation, and viii) policy factors.
- In (P. Smith et al., 2019), the authors discuss the functions delivered by a number of land-related CDRs (forestation, wetlands restoration, soil carbon sequestration, biochar, enhanced terrestrial weathering, and bioenergy with carbon capture and storage) with reference to climate mitigation, impact on ecosystem services, and Sustainable Development Goals (SDGs).

Cities may also consider the trilogy on i) research landscape and synthesis, ii) costs, potentials, and side effects, as well as iii) innovation and upscaling around negative emissions technologies published in 2018 in Environmental Research Letters (Fuss et al., 2018; Minx et al., 2018; Nemet et al., 2018).

### Annex 1. Temporary carbon removals

"Temporary carbon removal" defines CDR methods that store carbon for a limited period, typically ranging from a few years to several decades or centuries. Common options to tackle residual emissions from sectors involving short carbon cycle emissions, such as those from agriculture, biogas and biomethane production, and certain industrial processes involving biomass, include a range of biosphere-based carbon removal

methods. The list of territorial carbon reservoirs in **Box 44** and the land use categories listed in **Box 45** help navigate the different options and the relevant systems.

**Box 44.** Terrestrial carbon reservoirs (adapted from (WRI et al., 2022))

Carbon on land is stored in six main reservoirs:

— Above-ground biomass, i.e., living vegetation, both woody and herbaceous, above the soil, including stems, stumps, branches, bark, seeds, and foliage. About half of the dry weight is carbon, with the other half being water and other compounds.

— Below-ground biomass, i.e., live roots larger than a minimum specified size, commonly 2 millimetres in diameter. Smaller roots are often excluded because they typically cannot be distinguished from soil organic matter or litter. About half of the dry weight is carbon, with the other half being water and other compounds. The carbon in below-ground biomass is often approximately one quarter of above-ground carbon, but this varies from region to region (Huang et al., 2021).

— Deadwood, i.e., non-living woody biomass not contained in the litter. Deadwood includes standing deadwood, wood lying on the surface, dead roots, and stumps, larger than or equal to the maximum size set for litter (often 10 centimetres in diameter).

— Litter, i.e., all non-living biomass with a size greater than the limit for soil organic matter (usually 2 millimetres) and less than the minimum diameter chosen for deadwood (e.g., 10 centimetres), lying dead, in various states of decomposition above or within the mineral or organic soil. The maximum size for materials to be included in litter depends on the inventory.

— Soil, i.e., mineral soils up to a specified depth, usually 30 centimetres. Live and dead fine roots and dead organic matter (deadwood and litter) within the soil that are less than the minimum diameter defined for roots and dead organic matter are included in soil organic carbon where they cannot be distinguished from it empirically.

— Harvested wood products, i.e., all wood material (including bark) that leaves harvest sites. This includes products in use and in landfills (but not recycled wood products or biomass burned for energy capture). Products in use include end-use products that have not been discarded or otherwise destroyed. Examples include construction materials, wooden containers, and paper products. Products in landfills include discarded wood and paper placed in landfills, where most carbon is stored long term and only a small portion of the material is assumed to degrade at a slow rate.

In many cities, the single largest terrestrial carbon reservoir is aboveground biomass. The major exception is land with deep organic soils, like peat swamps or mangroves, where soil carbon may be dominant.

**Box 45.** Land use categories (IPCC, 2006, 2019a)

Settlements: All developed land, including transportation infrastructure and human settlements of any size.

Cropland: Cropped land, including rice fields, and agroforestry systems where the vegetation structure falls below the threshold for forest land.

Forest Land: All land with woody vegetation consistent with thresholds used to define forest land in national inventory.

Grassland: Rangelands and pastureland that are not considered cropland, and systems with woody vegetation and other non-grass vegetation that fall below the threshold for Forest Land.

Wetlands: Areas of peat extraction and land that is covered or saturated by water for all or part of the year.

Other Land: Bare soil, rock, ice, and all land areas that do not fall into any of the other five land use categories.

Common temporary carbon removal options are:

— **Afforestation and reforestation (A/R), forest ecosystem restoration, and improved forest management.** The first two terms refer to i) planting of new forests on lands historically dedicated to other use or restoration of the tree cover on minimally-covered lands, and ii) forests replanting on lands that contained forests in the past but were converted to other use.

  Borrowing from the IPCC land use categories (**Box 45**), afforestation entails a land use change from Non-Forest Land to Forest Land, while reforestation involve a two-step conversion from Forest Land to Non-Forest Land and then back to Forest Land. Reforestation of degraded land that previously supported forest ecosystems can have significant climate change mitigation effects. Mixed species reforestation efforts that focus on carbon sequestration can target ecosystem restoration by ensuring comparable physical, structural and functional characteristics to a reference forest ecosystem (SERA, 2021). Investing in afforestation and reforestation helps combating the opposite trend (i.e., deforestation) that, together with forest degradation, contributes to increasing GHG emissions (through e.g., associated forest fires) and to permanently removing carbon sink capacity, decreasing the climate change resilience of the affected areas, and substantially reducing their biodiversity (European Parliament and Council, 2023b). A/R differs from forest ecosystem restoration, which focusses on the ecological integrity and resilience of the forest ecosystem. When designed appropriately, this approach seeks to restore the ecological processes that enable self-sustaining and biodiverse ecosystems. Though many projects will entail some form of management over time, project designs that foresee indefinite human interventions to sustain them should not be seen as restoration projects as the pursued outcome is not a self-sustaining forest ecosystem (Palmer & Stewart, 2020).

  Improved Forest Management (IFM) (or regeneration) is different from A/R as it focusses on increasing the resilience of existing forest land by changing the management practices; there is no land use change or demand for land conversion. IFM can improve the carbon sequestration qualities and magnitude of natural sinks (IPCC Working Group III, 2022a). Specific measures include harvest rotations, harvesting timber selectively, pre-commercial thinning, direct local reforestation after tree felling, increasing planting density, active fertilisation, and genetic improvement (Sevillano et al., 2025).

Forestation and forest management processes are both critical to the magnitude and stability of carbon storage as they tackle different phases of the tree lifecycle. In a new forest, $CO_2$ sequestration mainly occurs through photosynthesis, resulting in carbon storage in above- and below-ground biomass (**Box 44**). In addition, carbon is sequestered in soils by the transfer from biomass through litter fall, dead roots and leaching from roots. The magnitude of carbon sequestration heavily depends on the tree species chosen, type of soil, forest management practices, climate, and moisture. It takes forests approximately 10 years to ramp up to the maximum sequestration rate and 20 to 100 years to reach maturity (i.e., saturation in terms of $CO_2$ removal). As the tree approaches maturity, the net uptake of $CO_2$ slows down, yet additional gains can be made (and reversals can be averted[20]) through improved forest management practices. Once mature, forest products can be harvested and the biomass stored in long-lived wood products or used for bioenergy with carbon capture and storage or biochar (see **Annex 2**). Consequent forest regrowth then allows continuing $CO_2$ removal (The Royal Society, 2018). The main resource limitation is land area as forestry competes with other social and economic land uses. The energy and water requirements are typically low along the whole lifecycle. Further, while initial costs of establishing plantations can be high, the costs of regeneration and management are comparatively low (The Royal Society, 2018). The impacts on the GHG balance and on biodiversity depend on the forest composition, design, location, as well as on the use of fuels, fertilisers and pesticides.

**Implementation options for A/R, forest ecosystem restoration, and IFM:**

- **Agroforestry**. Agroforestry is the intentional integration of trees and shrubs into crop and animal farming systems to create environmental, economic, and social benefits. It comprises alley cropping, silvipasture, riparian forest buffers, windbreaks, and forest farming. In alley cropping, trees are planted in rows and between the rows agricultural or horticultural crops can be grown to generate short-term (annual) income. Silvipasture is co-locating trees and livestock on a single piece of land, with trees providing timber, fruits, or nuts as well as wind shade and heat and rain shelter to the livestock. Riparian forest buffers utilise plantings of trees, shrubs, and grasses next to creeks, streams, and rivers to stabilise the banks from erosion and to filter farm nutrient runoff from going into waterways. Windbreaks are tree lines used to slow down wind to e.g., protect animals, crops, or buildings from wind, dust, odours, pesticide drifts, and snow. Forest farming uses existing forests to grow food, medicinal or herbal crops (e.g., ginseng, mushrooms) with some slight manipulation of the existing forest. As the principle whereby carbon removals occur is the same as forestation practices, for agroforestry to count as CDR, new trees have to be planted or forest manipulations need to lead to increased carbon uptake overall.

[20] It is worth noting that preventing loss of carbon storage capacity does not account as CDR (as there is no $CO_2$ removal from the atmosphere)

- **Silviculture**. Silviculture is a practice to increase the forest carbon stock. It refers to the growing and cultivation of trees to control the composition, structure, and dynamic of a given forest. Silvicultural practices include such interventions as site preparation, selection of forest species and genotypes, managing forest nutrients and residues, undergrowth control, prescribed fires, and targeted tree thinning. Different management practices will have different effects on the carbon stock, depending on characteristics like the type and age of the forest and on specific interactions between soil physical and chemical properties. Depending on the practice(s) selected, the net carbon effects may be positive or negative. A detailed understanding of the effects of management, climate and industry, should be combined with estimates of the impacts on forest ecosystems over time (Ameray et al., 2021).

- **Timber in construction** (see **Box 46**). Using forestry materials and engineered wood products (such as glued laminated timber, glulam, oriented stand lumber, cross-laminated timber, engineered bamboo) or their recycled version in the construction sector provides storage for the $CO_2$ captured in forests, extends the time of carbon storage of natural biomass and enables additional forest growth (The Royal Society, 2018). The climate benefit is only fully realised when the harvested trees are replanted and the forest biomass is restored to its original levels, resulting in an overall increase in carbon storage in both the forest and the harvested wood products. Not just hard wood, but also thermally and chemically treated soft wood could be used, with the benefit of faster growing cycles. The net positive effect on GHG emissions is hard to ascertain particularly in a lifecycle approach, with material substitution, end-of-life strategies (e.g., decommissioning of timber buildings), and carbon sequestration being decisive factors (Cordier et al., 2022). To maximise the sequestration potential, the materials should be reused, or burnt with CCS, although this may be difficult to ensure at scale (Gustavsson & Sathre, 2006). Planting new trees would come with varying land requirements and water consumption similar to those of forestation practices. Energy expenditures would be linked to harvesting, treating, processing and transporting wood. If the biomass used for building is imported, there will need to be an agreement on how and who claims the associated negative emissions. Double counting could also arise if the carbon removal is reported both at the time of carbon capture from the atmosphere via photosynthetic activity and in the year of biomass conversion to wood product/construction.

- **Bio-based products**. In a circular bioeconomy, bio-based products can support adaptation and mitigation, including carbon removal. Bio-based products have the potential to replace fossil-based products, such as plastics, concrete, steel and more, while extending the time that the carbon is sequestered in the biomass. The sustainability of bio-based products depends on the biomass feedstock, land management practice, climatic region, as well as the timing, scale and speed of deployment. The key to ensure a net–positive outcome is to maximise co-benefits and manage trade-offs through sectoral integration, transparency, and participatory governance models (IPCC Working Group III, 2022a). Using secondary biomass waste streams, such as organic consumer waste, agricultural harvest and forestry residues, can limit land use change risks compared to dedicated biomass production systems (Mouratiadou et al., 2020).

**Box 46.** Timber cities as carbon stores and co-benefits for urban net-zero

Many cities are turning to timber construction as a carbon capture and storage strategy, using buildings as long lived biogenic carbon pools and substituting high emission materials such as concrete and steel (Amiri et al., 2020; Arehart et al., 2021; Churkina et al., 2020). A large timber neighbourhood in the Mission City of Munich, with 566 flats, stores about 12.5 $ktCO_2$ over a 50-year life, illustrating how site scale planning requirements for wood can create measurable urban carbon stocks (Hafner et al., 2020). In Santiago de Chile, the expansion of timber buildings over eight years increased biogenic carbon stored in the urban fabric to about 200 ktC (≈10.8 $ktCO_2$), conceptualised as a "second forest" that transfers forest carbon into the city (Victorero & Bustamante, 2025). Scenario analysis for Auckland shows that maximising timber in new developments could help achieve a 40% $CO_2$ mitigation target around 20% faster while accommodating growth (Stocchero et al., 2017). At regional scale, a shift to timber buildings in Europe could capture 1–55 $MtCO_2$ per year by 2040, up to ~47% of current cement sector emissions, depending on market penetration and timber intensity (Amiri et al., 2020; Churkina et al., 2020). Beyond Munich, other Mission Cities are actively exploring the potential of using buildings as distributed carbon sinks, including Lahti (Finland), Grenoble-Alpes Metropole, Dunkirk (France), Differdange (Luxembourg), Amsterdam (The Netherlands), Ljubljana (Slovenia), Oslo (Norway), and Glasgow (United Kingdom). For instance, Lahti is driving wood construction forward by assessing its current state, developing new calculation and monitoring methods, and promoting its use in public buildings and apartment blocks. To support this effort, property owners and builders receive guidance and encouragement to adopt wood in their construction projects.

Beyond carbon, cities report multiple co-benefits from mass timber. Lifecycle assessments show 20–40% lower embodied emissions than comparable concrete or steel buildings, with additional delayed emissions through in-use carbon storage (Chapagain & Crovella, 2025; Dzhurko et al., 2024; Hemmati et al., 2024). Timber systems enable prefabrication and lighter structures, which are associated with faster construction, reduced site disturbance and waste, and lower noise during building and renovation works in dense neighborhoods (Liu et al., 2025; Tupenaite et al., 2023). Reviews of glulam and mass timber buildings highlight reduced construction time and costs, higher degrees of off-site fabrication, and circular economy opportunities via reuse, recycling and cascading of wood components (Liu et al., 2025; Tupenaite et al., 2023). Timber-based urban development can also support local employment and value chains in forestry, manufacturing and design; in Europe, expanded wood construction is estimated to create in the order of one million jobs along sustainable forest and timber supply chains (Liu et al., 2025). Indoor environmental quality benefits - such as improved perceived comfort and wellbeing in wooden interiors - are also reported, although still less quantified than climate benefits (Liu et al., 2025; Tupenaite et al., 2023).

However, benchmark analyses and scoping reviews stress that buildings-as-carbon-sinks are not a silver bullet: benefits depend on sustainable forest management and end of life practices, and increased timber demand can create land use and biodiversity trade-offs if not governed carefully (Arehart et al., 2021; Gibson & Pomponi, 2025; Mishra et al., 2022; Zatta, 2025). The most robust mitigation gains come when urban timber strategies are explicitly linked to i) verified sustainable forest management and additional forest carbon stocks, ii) high timber use intensity per square metre in long-lived buildings, and iii) circular design that extends service life and reuses components (Arehart et al., 2021; Churkina et al., 2020; Mishra et al., 2022; Victorero & Bustamante, 2025).

— **Revegetation**. Revegetation is a direct human-induced activity to increase carbon stocks on specific sites through the establishment of vegetation at a scale that does not meet the definitions of afforestation and reforestation (IPCC, 2003). Revegetation activities include i) reclaiming or restoring herbaceous ecosystems on degraded or carbon-depleted soils; ii) the establishment of vegetation cover on disturbed construction sites or mined lands; iii) planting of trees, shrubs, grasses or other non-woody vegetation on various types of land; and iv) marine revegetation (see "blue carbon management" below). Common revegetation measures relate to increasing woody biomass outside forests, e.g., in perennial crops, hedgerows, small islands of forest, shrublands, and urban trees as parks, gardens or roadside trees (Institute for European Environmental Policy, 2015). Trees on non-forest land sequester carbon dioxide just like trees on forested land; however, the area coverage is typically limited and local land conditions may not favour a healthy growth, thus impacting the magnitude of sequestration. Even if the CDR effect may be limited, revegetation and, in particular, urban trees produce indirect emissions reductions, by e.g., moderating the heat island effects and thus the amount of energy that is required for building space cooling. Carbon dioxide concentration due to vehicular emissions can also be reduced owing to the cooling action of roadsides trees. It is for this set of effects that revegetation is an important element of a city climate neutrality action plan: the magnitude of residual emissions would be reduced and a contribution to compensation may be provided (Fares et al., 2017; Onyili et al., 2023). The selection of different tree species with high biomass and efficiency of trapping and fixing carbon is recommended in revegetation programmes in urban areas when the CDR effect is to be maximised.

— **Soil carbon sequestration (SCS)**. SCS consists in changing land management practices to increase the soil carbon content. SCS can be applied to all managed land[21] without changing its current use and without requiring significant additional energy and water (but for processes involving increased irrigation). The carbon sequestration capacity varies considerably across options, with saturation (i.e., no additional sequestration) expected after a decade or two. The storage is highly prone to reversal and practices need to be maintained indefinitely, incurring yearly costs (The Royal Society, 2018). Further, while the impact on methane emissions is negligible, SCS may stimulate $N_2O$ emissions by increasing the organic nitrogen levels in the soil.

**Implementation options for SCS:**

- **Agricultural practices**. For croplands, options include i) crop management (i.e., improved varieties and their rotation, use of 'cover crops', perennial cropping systems, and agricultural biotechnology), ii) nutrient management (i.e., optimised fertiliser type, application rate, timing, precision application), iii) reduced tillage intensity and residue retention, and iv) improved water management (including drainage of waterlogged mineral soils).

[21] The IPCC defines managed land as "land on which human interventions and practices have been applied to perform production, ecological, or social functions". The concept of managed land was developed to separate anthropogenic from natural effects on GHGs. Within urban administrations and for the purpose of this guidance, all urban land is intended as managed.

- **Pasture management**. For grasslands, options include i) vegetation management (improved grass varieties, deep rooting grasses, increased productivity, and nutrient management), ii) animal management (stocking density, improved grazing management, improved animal feed production), and iii) fire management (The Royal Society, 2018).

— **Terrestrial wetlands restoration**. Wetland systems are important ecosystems for the sequestration of atmospheric $CO_2$ (Villa & Bernal, 2018). Their high carbon sequestration rate is caused by the high carbon stock per unit area of wetland soil (Nath et al., 2024). Wetland carbon sequestration qualities are determined by the presence and species of specific wetland vegetation, water levels and dynamics, and other ecological patterns. Among wetlands, peatlands (i.e., a type of freshwater wetland with an accumulation of partly decomposed plant matter) are the largest terrestrial storage of organic carbon, and improving peatland management is an important aspect contributing to climate change mitigation, biodiversity protection, and soil erosion reduction (European Parliament and Council, 2023b). These carbon stocks are vulnerable to release as a result of degradation, drainage and exploitation, hence projects tend to protect and restore existing wetlands, create new wetlands, or strengthen the carbon sequestration capacity (Y. Zhang et al., 2025). Wetland conservation/protection does not represent a CDR per se as it entails securing existing carbon stocks; however, wetland strengthening and restoration would enhance carbon stocks by scrubbing $CO_2$ directly from the atmosphere[22]. Further, artificial wetlands can be created and this would also count as CDR. However, creation is only possible on a site where conditions exist that can produce and sustain a wetland. Consequently, creation is more difficult than restoration. Restoration is typically obtained by rewetting the ecosystems by blocking drainage, among accompanying measures[23]. It has been identified as effective in turning wetlands into carbon sinks rather than sources, but can have a delayed net cooling effect, with time for cooling only to be realised after 200-500 years due to the initial release of methane (Mitsch et al., 2013) and nitrous oxide during the restoration activity and their warming effects. $CH_4$ emissions can go far beyond typical emission rates from natural peatlands if nutrient-rich peatlands are rewetted, if rewetting leads to permanent flooding and nutrient-rich organic sediment forms at the bottom of the newly formed water body, and generally if the water table is near the surface and vegetation is maladapted to wet conditions (Institute for European Environmental Policy, 2015). A restored wetland also faces the risk of impermanence if disturbed by human activity or natural disasters. Further, just like other habitats, wetlands will eventually reach a carbon equilibrium, although over a longer period of time than soil. Energy requirements are negligible, land requirements are lower than those of other natural sinks, yet water requirements exhibit large variability (The Royal Society, 2018).

[22] However, once wetlands are restored their conservation and protection becomes critical to avoid reversals.

[23] Drainage is the direct human-induced lowering of the soil water table and rewetting is the direct human-induced partial or total reversal of drainage.

— **Blue carbon management**: Blue carbon refers to biological carbon sequestration in marine ecosystems. Carbon removal applications are mainly focused on coastal blue carbon management in the form of rooted vegetation in coastal wetlands, including tidal marshes, mangroves, seagrasses such as Posidonia, and macroalgae such as kelp. The role of blue carbon ecosystems conservation and restoration for carbon removal is still surrounded with uncertainty related to the measurability and verifiability of the carbon uptake over time, including due to the vulnerability of such ecosystems and their carbon sink function to climate change. Just like terrestrial wetlands, coastal wetlands also face the risk of impermanence if disturbed by human activity or natural disasters. In addition, sea-level rise may impact the permanence of saltmarsh storage, unless this habitat is allowed to migrate landward as levels rise (The Royal Society, 2018). However, the restoration of coastal blue carbon ecosystems has many other critical functions, such as for climate adaptation, coastal protection, food provision and biodiversity conservation (Williamson & Gattuso, 2022). The success of a blue carbon management technique therefore depends on the intended function and is closely connected to places, times, values, and the specific variations and suitability of designs and technologies (Sovacool et al., 2024).

**Implementation options for wetlands restoration, and blue carbon management:**

- **Revegetation** (see above).
- **Rewetting** (see above).

**Cities in the spotlight: Valencia and Vitoria-Gasteiz (Spain), Budapest (Hungary), Oslo (Norway) and Ljubljana (Slovenia), and Glasgow (United Kingdom)**

In its pursuit of net-zero emissions by 2030, Valencia will give priority to local emissions compensation, leveraging in particular natural sinks and nature-based projects (València, 2024). The intention is to protect ecosystems that have become essential to adapt to climate change (e.g., temperature regulation, flood prevention) and to guarantee equitable access to better health**. Four science- and innovation-based projects** are planned to develop the maximum carbon sequestration potential of **wetlands, soil, vegetation, sea afforestation**, and water management, with circular economy models associated with biowaste. Notable is the **Green Posidonia innovation project** which recognises the potential of utilising discarded Posidonia (a seagrass species) as a resource for generating energy, creating bio-stimulants, bio-insecticides, and compost, while also enhancing public awareness about the critical role of Posidonia meadows. A key component of the project includes a pilot scheme to replenish a marine nursery within the port.

Vitoria-Gasteiz's residual emissions strategy reveals a multifaceted effort to augment carbon sinks within the city and its bio-region (Vitoria-Gasteiz, 2024). It includes enhancing the city's carbon sink capacity through **forestry and agricultural activities**, as well as by leveraging **urban and peri-urban green** (land) **and blue** (water) infrastructure. The strategy also embraces the promotion of land use activities and sustainable practices, such as **conservation agriculture** and the use of **nature-based solutions** to increase $CO_2$ capture. Furthermore, the city aims to decarbonise the agricultural sector by improving the carbon sequestration potential of **regenerative agriculture and organic fertilisation**, and by increasing the sector's energy efficiency. The description of the potential carbon sequestration capacity includes quantitative estimations, with due consideration of species selection.

The Municipality of Budapest proposes a comprehensive carbon sequestration programme through urban greening and conservation efforts (Budapest, 2025). It includes **enhancing and developing park**

**infrastructures, regenerating floodplain forests and riparian habitats, greening of courtyards, roofs, and walls, preserving and expanding forest cover, planting and protecting trees in public spaces, renewing green spaces within residential areas, and developing green infrastructures within cemeteries, including the promotion of forest or tree burials.** Additionally, the city is implementing measures such as **reforestation and afforestation, greening of brownfields, enhancing existing green infrastructure, protection and sustainable management of existing forests, increasing forest areas, developing an outer green ring, renewal and replacement of public trees, greening courtyards, roofs and walls, wetland revitalisation, improving water connectivity and green corridors, revitalisation of natural assets of stream valleys and riverside, floodplain forest regeneration, rehabilitation, and habitats protection, and promoting the uptake of urban agriculture**. Overall, the city is considering a wealth of greening options, using all suitable urban surfaces, from brownfields to roofs, from riverside and watercourses to cemeteries, to maximise its carbon sequestration potential.

Oslo's City Council has approved 13 mitigation measures concerning the management of the city's forests, while the "**Oslo Trees**" project aims to plant 100,000 more trees (Oslo, 2025). Efforts will focus on increasing the cycle period prior to logging, determining the overall logging level and thinning intensity based on climate considerations, assessing more climate-optimal utilisation of timber from thinning, and continuing and further developing the work on **wetland restoration**. Restoring eelgrass in the Oslo Fjord will improve biodiversity and carbon uptake, while preventing land degradation and non-indigenous species proliferation.

Ljubljana's strategy stands out for breadth of solutions, which include **expanding forests and improving forest management, creating green roofs and facades, surface unsealing, establishing new green areas and urban parks, tree planting, restoration of field boundaries and riparian zones on Ljubljana's marshes, promoting timber in construction, expanding agricultural land adapted to climate change, establishing green mobility corridors and green parking areas, agroecology, agroforestry, regenerative farming, revitalisation and greening of courtyards and atriums, sustainable farming and agricultural practices, public orchards, community gardens, green vertical ecosystems, and rain gardens** (Ljubljana, 2024).

Finally, Glasgow's measures include **afforestation and reforestation, greening and rewilding, tree planting, effective use of vacant and derelict land sites, creation of new local nature reserves, street trees, green roofs, sustainable harvested timber, urban agriculture, and wetlands restoration, including peatlands** (Glasgow, 2025). The city promotes a range of initiatives and instruments to support its carbon sequestration efforts. The city has also developed a **local biodiversity action plan and open space strategy delivery plan**, which will investigate opportunities to increase and protect biodiversity. The city will take forward **30+ aspirational Local Nature Reserves** and increase investment in peatland restoration in the city region to enhance biodiversity and increase capacity for carbon sequestration.

## Annex 2. Permanent carbon removals

"Permanent carbon remova"l defines artificial means of removing carbon directly or indirectly from the atmosphere. Common options are:

— **Biochar**. Biochar is a stable and long-lived charcoal-like product, produced by pyrolysing biomass in an anaerobic environment at temperatures ranging between 300–800°C. In the process, the original biomass carbon is stored in a form that is relatively resistant to decomposition and that can stabilise organic matter added to the soil (Lehmann & Joseph, 2015), while potentially producing important co-benefits in terms of soil fertility, increased crop yields, reduced reliance on chemical fertilisers, energy co-generation during pyrolysis, and reduced stratospheric ozone depletion (Tisserant et al., 2022). Through controlled pyrolysis, the production of biochar imitates the geological organic carbon pathway by rapidly carbonising and transforming the biomass into inertinite maceral. The pyrolysis temperature influences the carbon sink quality of the biochar by arbitrating the degree of completion of the carbonation and transformation process. Biochar formed at temperatures over 550°C has been shown to lead to pure inertinite maceral (Sanei et al., 2024). This practice, at the watershed between natural and technological CDR, comes with a lower risk of reversibility compared to soil carbon sequestration. The net impact on $CO_2$ emissions largely depends on its lifecycle, considering multiple end uses (The Royal Society, 2018). Biochar may come with significant land requirements to produce the biomass; however, it could also be produced from waste biomass with the potential co-benefit of avoiding emissions of $CH_4$ and $N_2O$ from naturally decayed waste (Woolf et al., 2010) and facilitating zero-waste approaches and circular economy. Water is not significantly used and energy is overall produced in the pyrolytic production of biochar; however, water mixed with chemicals is used to scrub the polluting gases from the pyrolysis process and this generates wastewater that shall be treated (The Royal Society, 2018). Furthermore, biochar darkens the soil it is applied to, thus reducing the local albedo (i.e., the capability of a surface to reflect solar radiation) to an extent that largely depends on the original albedo and the biochar application rate. Analyses reveal a reduction of the overall climate mitigation benefit of biochar systems by 13–22% due to the albedo change as compared to analyses which disregard the albedo effect (Meyer et al., 2012). Biochar application to soil has the potential to increase or decrease soil methane emissions, with water management and soil PH being key influencing factors on the soil methane flux (Jeffery et al., 2016). Similarly, a significant impact of biochar on denitrification has been observed, with a consistent decrease in $N_2O$ emissions by 10–90% in 14 different agricultural soils (Cayuela et al., 2013). Co-benefits are context- and feedstock-dependent: it is important to integrate supply chain and soil emissions to ensure a net positive emission balance (Tisserant et al., 2022). Competition for biomass is likely to be a considerable constraint to biochar production (Weng & Cowie, 2025).

— **Bioenergy with carbon capture and storage (BECCS or BioCCS)**. BECCS or BioCCS are essentially the same concept and are often used interchangeably. Some sources distinguish BECCS as specifically focusing on biomass combustion for energy, while BioCCS has a broader context including biological sequestration and the use of $CO_2$ as a feedstock. For this reason, in the following this guidance refers to BioCCS. BioCCS involves capturing and permanently storing $CO_2$ from processes where biomass is converted into fuels or directly burned to generate energy. As discussed, because plants absorb $CO_2$ as they grow, this is a way of removing $CO_2$ from the atmosphere. The majority of the world's BioCCS facilities capture $CO_2$ from ethanol fermentation. This produces a high-purity $CO_2$ stream suitable for sequestration and typically only requires dehydration before compression for transport and geological storage (Global CCS Institute, 2021). Another example of BioCCS implementation is waste-to-energy plants (operating on municipal solid waste with a significant biogenic component) combined with CCS. This represents a pathway to carbon removal while producing power and handling waste, particularly relevant in urban environments (Global CCS Institute, 2021). This solution is becoming more economically attractive with the introduction of new technological processes like oxy-fuel combustion (Global CCS Institute, 2020a). BioCCS comes from a mix of natural and technological approaches and is currently the most mature of all the carbon removal technologies, as both bioenergy production and CCS have been separately proven at commercial scale (Global CCS Institute, 2021). Large-scale deployment is more uncertain (Anderson, 2015), but models indicate that BioCCS may be relatively inexpensive in the long term considering potential technology development and discounting rates (van Vuuren et al., n.d.). Regardless, the effects of bioenergy production on land degradation, albedo change, food insecurity, water scarcity, other GHG emissions and environmental goals, and displacement effects due to competing demand for energy and waste heat are scale- and context-specific (IPCC, 2019b). For instance, compared to pre-combustion, post-combustion, and direct air CCS, BioCCS is the technology that has the highest water footprint per tonne of $CO_2$ captured, largely due to the high water requirements associated with plant transpiration (Rosa et al., 2021). Further, a review of the literature identifies that the limiting factor for BioCCS is the supply of biomass (Global CCS Institute, 2019). Scaling up BioCCS will require the development of supply chains for sustainable biomass from the waste products of agriculture and forestry, and potentially significant areas of land for the cultivation of energy crops (Global CCS Institute, 2020b). Finally, as with timber in construction (see **Annex 1**), there is a two-sided risk of double counting linked to the claiming entity (if the biomass is imported) and to the step of the process the removal is associated with (i.e., the sequestration from the atmosphere by trees and crops or the biomass conversion to energy).

**Implementation options for biochar and BioCCS:**

- **Urban and industrial organic waste**. Urban and industrial organic wastes are potent feedstocks for biochar production and BioCCS plants. Feedstocks include municipal solid waste (MSW), industrial wastewater, sewage sludge, livestock, and poultry wastes. The production of biochar or energy using waste feedstocks can support carbon sequestration and sustainable waste management. Diversion of such waste streams, which often end up at a landfill, for biochar has limited risk of 'leakage' - an increase of GHG emissions elsewhere (see **Section 6.3**) - due to a diversion of feedstock for biochar production (Weng & Cowie, 2025). The same can be said for applying BioCCS to a waste-to-energy plant. On average, the waste streams flowing into such plants to incinerate consist of 60% biogenic content, representing a significant potential for the realisation of negative emissions (Larsen et al., 2013). Challenges for biochar production include the inconsistent composition, moisture content, and contaminants found in the waste feedstocks, which undermines the quality of biochar. In addition, there are logistical restrictions related to waste collection and processing that may prevent reaching the full potential (Ahmed et al., 2024). Challenges for BioCCS on plants involving the use of urban and industrial organic waste as a feedstock include the relative inconsistency of the supply and quality of the biomass, potentially high pre-treatment costs, and ensuring a balance between the lifecycle emissions of the process and the net climate benefits of $CO_2$ capture and storage.
- **Cropping and forestry residues**. Other feedstocks used to produce biochar or in biomass-to-power processes coupled with carbon capture technology include cropping residues, such as straw, husks, and cobs, and forestry residues, such as wood chips, bark, and brush. A challenge is that crop residues are often kept on site for soil moisture, controlling weeds and reducing land erosion risk, amongst others. As a result, using such residues could lead to leakage and a reduced net climate benefit (Weng & Cowie, 2025). Challenges of using cropping and forestry residues for BioCCS are related to supply chain, land use, energy efficiency, and costs (Babin et al., 2021) (see **Box 47**).
- **Purpose-grown biomass crop**. Using purpose-grown biomass crops for the production of biochar or in plants coupled with BioCCS requires a quantity of land available for dedicated biomass production. There are significant risks associated with the use of such crops, particularly in relation to biodiversity, food security and vulnerable communities. Land with the greatest potential for biomass use in biochar or BioCCS plants that ensures a net positive climate impact is former agricultural or pasture land not converted to forest or urban areas (Field et al., 2008) (see **Box 47**).

**Box 47.** On the use of crop residues and purpose grown biomass for CDR

Biomass-based CDR options such as BioCCS should be assessed vis-à-vis the sustainable supply of residues and dedicated crops and their potentially significant social ecological implications.

**Crop residues: waste reduction vs CDR feedstock**. Integrated assessment studies typically assume that only a fraction of agricultural residues can be removed while maintaining soil functions; residue removal beyond ecological limits risks soil carbon loss, erosion, and reduced yields (Daioglou et al., 2019; Vaughan et al., 2018). At the same time, global analyses indicate that, within ecological constraints, residues can be an important low-cost, low-land use feedstock for BioCCS, biochar and - beyond CDR options - anaerobic digestion with CCS, contributing several percent of global GHG compensation and reduction without additional land use change (Feng & Rosa, 2024; Lefebvre et al., 2023; Vaughan et al.,

2018). For biochar, using only forest and crop residues could deliver in the order of 6–10% of current global emissions in durable CDR while avoiding direct competition with food and habitat (Lefebvre et al., 2023; Tisserant & Cherubini, 2019). The key trade-off is therefore between leaving residues in situ to protect soils versus diverting part of this resource to energy and biochar systems that can lock up carbon and displace fossil fuels.

**Purpose grown biomass: restoration vs production**. Most 1.5–2 °C pathways deploy large areas of dedicated bioenergy crops, with some scenarios exceeding 100–150 EJ/year of primary bioenergy by mid-century (Daioglou et al., 2019; Patrizio et al., 2021). At these scales, land competition with food production, biodiversity, and other ecosystem services becomes acute (Boysen et al., 2017; Daioglou et al., 2019; Jones & Albanito, 2020). Spatially explicit modelling finds that even when limited to abandoned cropland and degraded land, terrestrial CDR from plantations is strongly constrained by future food demand, nature conservation needs, and albedo effects, and that converting natural ecosystems can yield higher CDR at the cost of major biodiversity losses (Boysen et al., 2017). Large scale BioCCS thus risks undermining Sustainable Development Goals via water use, land use change, and rural livelihoods (Brack & King, 2021; Daioglou et al., 2019; Fajardy et al., 2018). Conversely, carefully sited energy crops on marginal or degraded land, or integrated with agroforestry, can increase biomass supply, support rural income, and, in some contexts, enhance soil carbon (Daioglou et al., 2019; Y. He et al., 2024). There is also a tension between restoring and protecting forests as long-lived carbon sinks and biodiversity reservoirs versus intensively managing forests for harvested wood products and feedstock: increasing demand for forest biomass can displace timber markets and reduce carbon stored in slash and deadwood pools if residues are heavily harvested (Brack & King, 2021; Favero et al., 2023).

**Systemic risks and governance needs**. Whole system analyses show that BioCCS chains can range from clearly net negative to net positive emissions depending on land use change, fertiliser and energy inputs, and transport distances (Fajardy et al., 2018; Fajardy & Mac Dowell, 2017). Waste- and residue-only supply chains, decentralized BioCCS, and biochar pathways generally show lower land and water impacts and fewer social risks, but are limited by the finite availability of sustainable residues (Almena et al., 2022; Fajardy et al., 2018; Feng & Rosa, 2024; Lefebvre et al., 2023). Under weak governance, optimistic assumptions about biomass availability can delay gross emissions cuts and lock in over-reliance on future CDR that may not materialise (Brack & King, 2021; Jones & Albanito, 2020). Robust policy therefore needs to i) cap biomass use within verified sustainable potentials, ii) prioritise higher value mitigation or CDR uses of scarce biomass, and iii) integrate land based CDR with forest protection, food security, and biodiversity strategies (Brack & King, 2021; Daioglou et al., 2019; Patrizio et al., 2021).

— **Direct air carbon capture and storage (DACCS)**. $CO_2$ is removed from the atmosphere by placing large volumes of air in contact with chemicals (sorbents). Sorbents are treated so that the $CO_2$ is released from them, for sequestration in geological storage sites or for utilisation in the production of carbon-based fuels and other chemicals (Gambhir & Tavoni, 2019). DACCS itself does not require large portions of land but instead relies on proximity to abundant water and energy sources (Ozkan, 2021). According to a recent literature review (Garza et al., 2023), a plant can require up to seven tonnes of water per tonne of $CO_2$ removed, with fresh (not seawater) supply mandated for the air-sorbent contact stage. Land usage may be a concern when solar energy is used to supply an integrated DACCS plant. For a one-$MtCO_2$/year facility, the direct land required for the contactor units and the regeneration facility is approximately 2.5 hectares, exclusive of any indirect allocation for onsite energy generation from renewable electricity or natural gas power plants (Garza et al., 2023). Further, DACCS processes have high energy or heat requirements that could be partially alleviated if integrated with other systems (e.g., industrial processes that emit waste heat) (The Royal Society, 2018). DACCS are also associated with requirements (and risks) in terms of storage (capacity and integrity) and transport of $CO_2$ at high pressure. Finally, the impacts of DAC sorbents and process co-products should be carefully studied throughout their entire lifecycle. Refer to **Section 5.1.1** for urban-specific deployment of direct air capture modules.

**Implementation options for DACCS:**

- **Solid sorbents**. $CO_2$ is removed through adsorption whereby the $CO_2$ molecules adhere to the surface of a solid sorbent material. Technological options include supported amine absorption, in which air is passed through a high-surface porous material with chemicals called amines (also routinely used for CCS) and heated to release $CO_2$ as saturation is reached. Another option is the lime-soda process, which involves a suite of chemical processes among sodium hydroxide (NaOH), $CO_2$, and lime (CaO) (The Royal Society, 2018). Compared to liquid sorbents, solid sorbents tend to be less prone to degradation and can be designed for higher cycling stability to use repeatedly without significant loss of performance (Duan et al., 2023).
- **Liquid sorbents**. $CO_2$ is removed via absorption by dissolving it into alkaline or amine-based liquid sorbent materials such as monoethanolamine (MEA) and potassium hydroxide (KOH). Technological options include artificial trees, where a large, exposed surface area of carbon adsorbing material is brought to saturation and the $CO_2$ stream is released by humidifying and soaking the sorbent (The Royal Society, 2018). Liquid sorbents tend to have a greater potential for regeneration at lower temperatures compared to solid sorbents. They often have a higher capacity to absorb larger quantities of $CO_2$, and they are easier to handle and process.

— **Enhanced Rock Weathering (ERW).** Weathering is the natural process through which rocks and minerals break down or dissolve. An input to this process is $CO_2$ from the atmosphere. Artificially accelerated weathering is a chemical approach to radically amplify the amount of $CO_2$ removed from the atmosphere and speed up the process. This manipulation can be accomplished by enhancing one or more of the factors that control the weathering process, typically the reactive surface area, the amount of weathering rocks, and/or the rate of dissolution. This may produce co-benefits in terms of nutrients availability, soil hydrological properties, and enhanced food production and its terrestrial application at scale would be feasible with existing farm equipment. Further, enhanced weathering on cropland requires no additional land and can be co-deployed (for example) with the feedstock for BioCCS and biochar to increase the sequestration potential per unit of land area (The Royal Society, 2018). Potential side effects of enhanced weathering affect health, as there may be a release of toxic mineral outputs, heavy metals or particles of respirable size, and relate to the demand for energy and infrastructure (EPRS, 2021). Further, the impacts on soil microbial and marine biodiversity remain to be determined (Edwards et al., 2017).

**Implementation options for ERW:**

- **Silicate rocks**. Dusting large amounts of the Earth's surface (land, coastal areas or ocean waters) with finely ground, highly reactive, silicates would increase the weathering of rocks and minerals, particularly if coupled with biotic aids (such as certain plant varieties) (Lawford-Smith & Currie, 2017). Suitable rocks, particularly silicate and carbonate minerals rich in calcium and magnesium (such as olivine-rich ultramafic and mafic rocks or basaltic rocks) need to be mined, crushed, transported and dispersed. Costs could be contained by using waste materials, such as mine tailings or industrial by-products from iron and steel production (e.g., steel slag or cement kiln dust), which, however, may release pollutants with harmful effects (Kelemen et al., 2019; Renforth, 2019).

— **Mineral carbonation.** Mineral carbonation is recognised as an accelerated form of naturally occurring weathering of silicate rocks. It is a technology solution that aims to safely and permanently sequester $CO_2$ from smaller/medium emitters (typically facilities releasing tens to hundreds of thousands of tonnes of $CO_2$ per year, such as waste-to-energy plants or district heating units), where geological sequestration is not a viable option. In mineral carbonation processes, $CO_2$ chemically reacts with calcium- and/or magnesium-rich minerals to form stable carbonates. The reaction can take place either below (in situ) or above (ex situ) the ground. In situ mineral carbonation involves the injection of $CO_2$ into underground reservoirs to promote the reaction between $CO_2$ and alkaline-minerals present in the geological formation to form carbonates. Ex situ mineral carbonation relates to above-ground processes, which require rock mining and material comminution as pre-processing (Sanna et al., 2014; The Royal Society, 2018). Most demonstrations of mineral carbonation have relied on a $CO_2$-rich gas from industrial and power plants hence from fossil, not atmospheric, sources (Gadikota, 2021). Such processes would contribute to the overall emissions reduction target, but do not represent a form of residual emissions compensation (this distinction is also made in IPCC AR6 WGIII and the EU CRCF Regulation). Conversely, carbon mineralisation with DAC would serve as CDR.

— **Ocean alkalinity enhancement (OAE)**. It involves increasing seawater alkalinity to provoke a more rapid uptake of atmospheric $CO_2$. These techniques thus stimulate atmospheric $CO_2$ removal downstream of their activity (Halloran et al., 2025). Artificially alkalising seawater can be achieved through a range of techniques, such as i) the dispersal of alkaline minerals from ships, platforms, or pipes; ii) the direct injection of alkaline liquid into the surface ocean (i.e., dissolving alkaline minerals or materials prior to adding them to seawater); iii) the addition of minerals to coastal environments; and iv) the electrochemical removal of acid from seawater (Eisaman et al., 2023). There are large synergies with terrestrial enhanced weathering, as the dissolution of alkaline minerals upstream from the ocean (i.e., EW) can be conveyed to the ocean through runoff and river flow (Babiker et al., 2022; Renforth & Henderson, 2017). Alongside atmospheric $CO_2$ uptake, OAE has been suggested to positively contribute to limiting ocean acidification, thereby having the potential to decrease risks to ocean ecosystems (Bach et al., 2019). However, a deep understanding of long-term as well as local impacts, potential ecological risks and feedback mechanisms associated with large-scale OAE deployment is still missing (Kowalczyk et al., 2024). Additionally, verifying the atmospheric carbon removal resultant from OAE techniques is challenging, as there are large uncertainties and data gaps (e.g., air-sea gas exchange, ocean currents, carbonate chemistry) (Berger et al., 2024; Halloran et al., 2025; Schulte et al., 2024).

  **Implementation options for OAE**

  - **Carbonate rocks**. OAE methods involve adding alkaline materials to seawater. This includes carbonate rocks such as limestone and calcite, and alkaline-rich industrial waste products (Kwiatkowski et al., 2023). Carbonate rocks tend to dissolve quicker than silicate rocks, but may be less effective over longer periods of time due to a propensity for precipitation in the ocean (National Academies of Sciences Engineering and Medicine, 2022).
  - **Silicate rocks**. This includes silicate rocks such as olivine and basalt. Silicate rocks tend to be considered more efficient for permanent sequestration as they consume higher amounts of $CO_2$ per unit of alkalinity produced. It is moreover less likely to be counteracted by carbonate precipitation.

— **Artificial Ocean Fertilisation (AOF).** This method accentuates 'the biological pump', a process of vertical transport of $CO_2$ from surface to deep ocean, activated by surface-level photosynthetic activity. In natural systems, this downward flow is nearly balanced by the upward return of respired carbon from the deep ocean. However, AOF accentuates the biological pump effect (and thus the carbon sequestration) by acting on its limiting factor: the availability of photosynthesising life in the surface ocean (e.g., plankton) which in turn is limited by the supply of either micronutrients (e.g., iron) or macronutrients (nitrates and phosphates). AOF demands energy, raw materials, and water (significant requirements where nitrates are used) for the production of nutrients, their transport and distribution (chemical plants and ships). The resources required are significantly lower for iron fertilisation as compared to nitrate/phosphate fertilisation. Further, concerns exist on the potential unintended consequences of ocean fertilisation, such as changes in ocean chemistry and the potential for harmful algal blooms (Powell, 2008). Additionally, there is a lack of long-term monitoring and research on ocean carbon sequestration, and the cost of large-scale implementation is still uncertain.

**Implementation options for AOF:**

- **Iron fertilisation**: Iron fertilisation focusses on adding iron to areas where it is a limiting nutrient. The technical feasibility of iron fertilisation has been demonstrated and the stored carbon could potentially be retained for centuries to millennia, with continued fertilisation limiting the effects of the eventual natural return to the surface. However, while clear plankton blooms have been observed, the transfer of extra carbon to the deep ocean varies significantly between experiments and is, in any case, limited by the upward return flux (The Royal Society, 2018).
- **Nitrogen and phosphorus (N&P):** N&P fertilisation targets areas where nitrogen or phosphorus are limiting. It involves adding nitrogen and phosphorus, which are macronutrients essential for phytoplankton growth, to areas where they are depleted. N&P may not be as efficient as iron fertilisation in regions where iron is the primary limiting nutrient.
- **Enhanced upwelling**: Ocean fertilisation through enhanced upwelling aims at stimulating the growth of phytoplankton by 'pumping' nutrient-rich deep ocean water to the surface. This process can potentially lead to increased carbon sequestration as phytoplankton absorb carbon during photosynthesis. The efficacy of enhanced upwelling in fostering greater sequestration of carbon requires further research (Jürchott et al., 2024).

Overall, while robust monitoring and verification is still needed to ensure that $CO_2$ does not leak out (where relevant), permanent sinks are generally much more inert and secure than temporary carbon sinks (M. Allen et al., 2020). Moreover, technological approaches like BioCCS and DACCS can offer advantages over natural solutions, including (Global CCS Institute, 2021; International Energy Agency, 2020):

— The invulnerability to weather events;

— The zero risk of fires that can release $CO_2$ stored in biomass into the atmosphere; and,

— In the case of DACCS, the much lower land area requirements.

However, at the current level of knowledge and application, all these technologies face a variety of economic, biophysical and ecological constraints that may limit their use and their net positive effect.

**Cities in the spotlight: Stockholm, Helsingborg, Malmö (Sweden) and Oslo (Norway)**

To achieve its goal of becoming climate positive by 2030, Stockholm is implementing carbon dioxide removal activities within the city's boundaries (Stockholm, 2025). Following a pilot phase, a large-scale **BioCCS** facility linked to a biofuel-fired combined heat and power plant is anticipated to be operational by 2025/2026, with the capacity to generate 800,000 tonnes of negative $CO_2$ emissions annually. The EU Innovation Fund has already granted €1.1 billion to the project. A portion of the negative emissions will be financed through sales to private entities, necessitating a system to prevent double counting. Even though the capacity of the BioCCS facility would remove more than what would be strictly needed to achieve net-zero emissions, the city is explicitly committed to continuing efforts to further reduce its emissions. The city is also leveraging **biochar** produced from repurposed garden waste to enrich the soil in urban gardens and street-side tree plantings, thus boosting the growth of trees and shrubs. Additional co-benefits the city intends to harness are improved management of stormwater, lowered urban temperatures, and an overall

enhancement of the city's liveability. Additionally, the surplus heat generated during the production of biochar is fed into the district heating network, further aiding in the diminishment of remaining emissions.

Helsingborg's approach to carbon sequestration encompasses a wide range of measures with a focus on technological and durable sinks (Helsingborg, 2025). It includes the implementation of a **BioCCS** facility at the cogeneration plant, the use of **DACCS**, the production of **biochar**, and the restoration and creation of forest land and shelterbelt plantations. Notably, Helsingborg has established a competence centre for biochar and is working to expand production and encourage the use of biochar in agriculture and other sectors. Additionally, Helsingborg is promoting changed agricultural practices on agricultural land, rewetting of organogenic soils, and the increase of seaweed and eelgrass meadows. The city is also preserving and developing existing carbon sinks in sea, soil, and vegetation, and creating new parks and green areas. Helsingborg's comprehensive strategy to address carbon sequestration is underpinned by solid quantification and scenario analysis to fully compensate for all residual emissions by 2030. The analysis has identified a range of options for reducing emissions and increasing carbon sinks. The city has quantified its carbon sink potential, with an estimated total carbon sink of approximately 124,000 $tCO_2$ (100,000 from technological sinks, the rest from biochar and natural sinks).

Similarly, Malmö's Action Plan outlines a wide range of compensation mechanisms, such as green infrastructure, soil carbon sequestration, **biochar**, biomass in construction, and **BioCCS** (considered for both the waste-to-energy plant and district heating) (Malmö, 2024). The city is experimenting with biochar in various municipal applications and has partnered with the main biochar innovation and development project in Sweden.

Oslo's strategy for addressing residual emissions combines technological and natural solutions (Oslo, 2025). The upcoming **CCS installation at the waste facility** Klemetsrud - set to launch in 2027 – is designed to capture 170,000 tonnes of biogenic $CO_2$ through BioCCS, enabling Oslo to become carbon negative by 2030. Oslo will nevertheless continue working on reducing its emissions and brings forward an exemplary portfolio of actions for natural sinks preservation and expansion, without expecting any contribution to residual emissions compensation.

## Annex 3. Removal of other GHGs

The removal of non-$CO_2$ GHGs, such as methane ($CH_4$), nitrous oxide ($N_2O$), ozone-depleting halocarbons, and short-lived fluorinated gases (HFCs, PFCs and $SF_6$), has the potential for rapid material effects on global warming. The lifecycle of such GHGs in the atmosphere is significantly shorter than carbon.

The Global Warming Potential (GWP) of a GHG quantifies its heat-trapping ability relative to $CO_2$ over a specific time period, typically 100 years. Different GHGs have different GWPs. **Figure 9** below shows that 1 ton of methane emitted related to fossil fuels is equal to approximately 30 tons of $CO_2$. Moreover, the short-term climate impact of methane over a period of 20 years has been estimated to be up to 86 times higher than $CO_2$ (Myhre et al., 2014).

**Figure 9**. GWP values for 100-year time horizon for major GHGs.

| Common chemical name or industrial designation | Chemical formula | GWP values for 100-year time horizon | | |
|---|---|---|---|---|
| | | Fourth Assessment Report (AR4) | Fifth Assessment Report (AR5) | Sixth Assessment Report (AR6) |
| **Major Greenhouse Gases** | | | | |
| Carbon dioxide | $CO_2$ | 1 | 1 | 1 |
| Methane – non-fossil | $CH_4$ | 25 | 28 | 27.0 |
| Methane – fossil | $CH_4$ | N/A | 30 | 29.8 |
| Nitrous oxide | $N_2O$ | 298 | 265 | 273 |
| Nitrogen trifluoride | $NF_3$ | 17,200 | 16,100 | 17,400 |
| Sulfur hexafluoride | $SF_6$ | 22,800 | 23,500 | 24,300 |

*Source: (Greenhouse Gas Protocol, 2024). Adapted from IPCC 4th, 5th and 6th Assessment Reports.*

The GWP of different GHGs therefore implies different contributions to global warming. According to the World Meteorological Organization (WMO), $CO_2$ contributed approximately 64% to the global warming effect in 2022, whereas methane about 19%, and nitrous oxide 7% (WMO, 2023). This signals a significant contribution of non-$CO_2$ GHGs and the limitations of a $CO_2$-only focus (de Richter et al., 2017). As a matter of priority, reducing non-$CO_2$ GHGs such as methane in addition to the reduction of $CO_2$ emissions can have a disproportionately large effect in slowing down future global warming (Shindell et al., 2024).

The trend-breaking increase in methane emissions in the first half of this decade could be attributed to a large extent to fossil fuel use and the degradation of wetlands as a result of global warming (Shindell et al., 2024). According to the United Nations Environmental Program's global methane assessment, currently available solutions have the potential to reduce methane emissions by 30% in 2030 (UNEP, 2021). However, only about 13% of global methane emissions are covered by current policy mechanisms (Olczak et al., 2023). The Global Methane Pledge, signed by the EU and over 150 other nations with the objective of a 30% reduction in emissions from oil and gas by 2030 compared to 2020 levels, has the potential to significantly slow down emissions, but effective international cooperation is a necessary condition (Bessagnet et al., 2024).

Meanwhile, strategies for the removal of non-$CO_2$ gases can offer quicker and more effective warming reduction than $CO_2$ removal efforts which are focused on long-term carbon cycle processes. The removal of non-$CO_2$ GHGs is however at an early stage, with atmospheric methane removal (AMR) being the most prominent focus of research and innovation efforts. AMR research examines a wide range of technological approaches, including methane reactors and concentrators, surface treatments, ecosystem uptake enhancement, and atmospheric aerosol enhancement. All these techniques aim to break down methane into $CO_2$, a far less potent GHG (Jackson et al., 2021; Ming et al., 2022). The destruction of methane by oxidation to $CO_2$ can eliminate about 97% of the warming impact on a 100-year time scale. Under certain conditions, such as environments with a large concentration of methane in the air, AMR may even be competitive with more direct efforts to reduce methane emissions (Nisbet-Jones et al., 2022). The greatest challenge to AMR is the relatively low average methane concentration of 2 ppm, compared to the significantly higher atmospheric concentration of $CO_2$ at approx. 420 ppm. In addition to atmospheric methane being much more diluted, it is also chemically less reactive at such low concentration levels. Further research and demonstration is needed to identify effective mechanisms for AMR at low

concentration levels (German Environment Agency, 2024). If AMR proves feasible at scale, its large GWP highlights the potential for slowing the near-term rate of global warming.

Technological methane removal is still in the early stages of development, but enhancing the methane sequestration capacity of natural ecosystems such as swamps, wetlands, and tropical forests, is readily available today (Gauci et al., 2024). The potential impact is significant, with researchers finding that the restoration of forest and grassland could increase methane uptake by 90.0% and 30.8%, respectively, and wetland restoration by 544.4% (T. He et al., 2024). This indicates an additional benefit to cities considering certain ecosystem restoration approaches as part of their residual emission strategy.

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