Monitoring, Reporting and Verification of Greenhouse Gas Removals

Task and Finish Group Report

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Executive Summary

The context

The UK Government (HMG) is committed to decisive action to cut emissions across the economy, to achieve our target of net zero emissions by 2050. To complement these efforts the Climate Change Committee has been clear[1] that Greenhouse Gas Removal (GGR) methods will be required to offset residual emissions in sectors that are difficult to decarbonise completely.

The permanent removal of greenhouse gas emissions (GHG) is key to reaching net zero. For a GGR approach to be credibly 'net-negative' it must remove more GHGs from the atmosphere than it creates and store it for an effective period of time.

It will therefore be necessary:

- To be able to quantify, robustly and transparently, the amount and permanence of removals,
- To develop appropriate monitoring, reporting and verification protocols for a range of GGR approaches, which can enable a GGR project to be completed,
- To ensure genuine climate benefits and that plans for GGRs are aligned to the UK's climate adaptation needs.

About the Task and Finish Group

BEIS convened a GGR monitoring, reporting and verification (MRV) Task and Finish Group ('The Group') with the aim of understanding:

- The current position on MRV for negative emissions in the UK,
- Existing regulatory frameworks and standards,
- The gaps that exist and the work required to fill them,

to develop a comprehensive and robust approach to MRV that will support the development and delivery of GGRs.

The role of the Group is advisory and, whilst they have been actively consulted throughout and have reviewed this report, they have not been asked to endorse its contents.

Over the course of four months, we engaged with 11 experts from a range of institutions, along with government officials, in two group meetings. The Group's members represent industry,

[1] CCC (2019) Net Zero – The UK's contribution to stopping global warming

academics, the financial sector, international organisations, the legal sector, representative organisations, and HMG science advisors and policy officials.

We also held one-to-one meetings with a further 13 stakeholders on deep-dive topics, to understand specific aspects of MRV and its application to particular GGR approaches in more detail.

This report elaborates on the discussions and presentations from the group meetings, as well as the one-to-ones.

Key messages / recommendations

1. Permanence and durability of CO2 storage is key and a permanent GGR can be considered inherently more valuable from a climate repair perspective than a non-permanent option. To address the issue of leakage or reversal, the concept of a partial or discounted credit should be introduced.

2. If a non-permanent CO2 store leaks earlier than expected, the leaked CO2 will have to be “re-removed” in the future. Provision for this future re-removal should made at the outset. Liability for the provision of this “re-removal” capability should sit with the initial off-setter.

3. It is important to distinguish between avoided and removed emissions. A lifecycle assessment of the entire GGR supply chain is essential to show that the total quantity of atmospheric CO2 removed and permanently stored is greater than the total quantity of CO2 emitted to the atmosphere.

4. HMG should develop detailed MRV protocols for each GGR approach, in parallel with initial commercial demonstration.

5. Establish, by 2024, an independent function to sit between project developers and HMG. This function should be responsible for the creation and administration of an independent MRV regime to ensure that the amount and permanence of removals are quantified, robustly and transparently.

Introduction

Delivering Net Zero

For the UK to reach net zero emissions in 2050, Greenhouse Gas Removal methods (GGRs)[2] will be required to balance residual emissions from some of the most difficult to decarbonise sectors, such as industry, agriculture, and aviation. Analysis from the independent Climate Change Committee (CCC) supports this position.[3]

The important role of GGRs in global efforts to tackle climate change has been recognised by the Intergovernmental Panel on Climate Change (IPCC). In 2018, the IPCC's landmark Special Report on the impacts of global warming of 1.5°C noted: "All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal on the order of a cumulative total of 100–1000 GtCO2 over the 21st century."[4]

- As illustrated in Figure , GGR is part of a portfolio of response options to anthropogenic climate change. Importantly, GGRs are not a substitute for decisive action across the economy to cut emissions and HMG's priority is to tackle the root cause of climate change by reducing emissions of greenhouse gases from human activities whilst adapting to those impacts that are unavoidable. GGR is intended to address emissions that are currently impossible, or prohibitively expensive to directly abate.

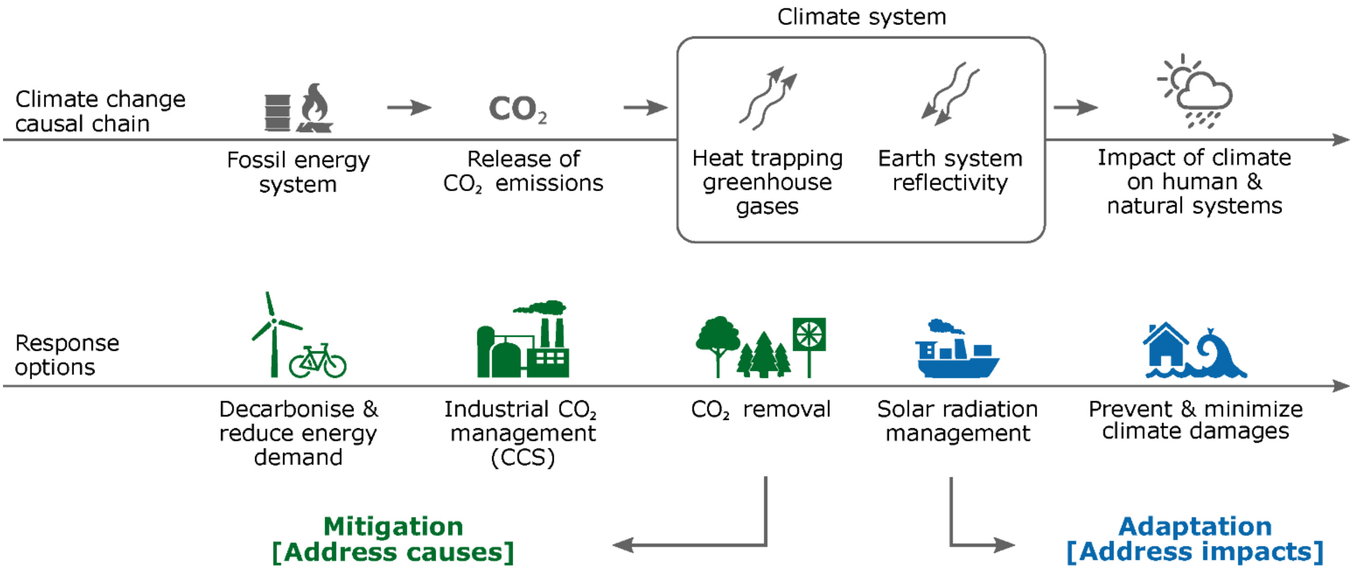


Figure 1: Illustration of the role of GGR in the context of mitigating and adapting to climate change. Image from Minx et al5.

[2] GGRs is the name given to a group of methods that directly remove greenhouse gases from the atmosphere.
[3] CCC (2019), Net Zero – The UK's contribution to stopping global warming.
[4] IPCC (2018), Summary for Policymakers – Special Report on the impacts of global warming of 1.5°C, p.19
[5] Minx et al, Environ. Res. Lett., 2018.

There are a range of approaches that may be counted as GGRs, which fall broadly into two categories:

- **Nature-based approaches**: such as afforestation, forest management, and soil carbon sequestration.
- **Engineering-based approaches**: such as Direct Air Carbon Capture and Storage (DACCS), Bioenergy with Carbon Capture and Storage (BECCS), wood in construction, biochar, and enhanced weathering.

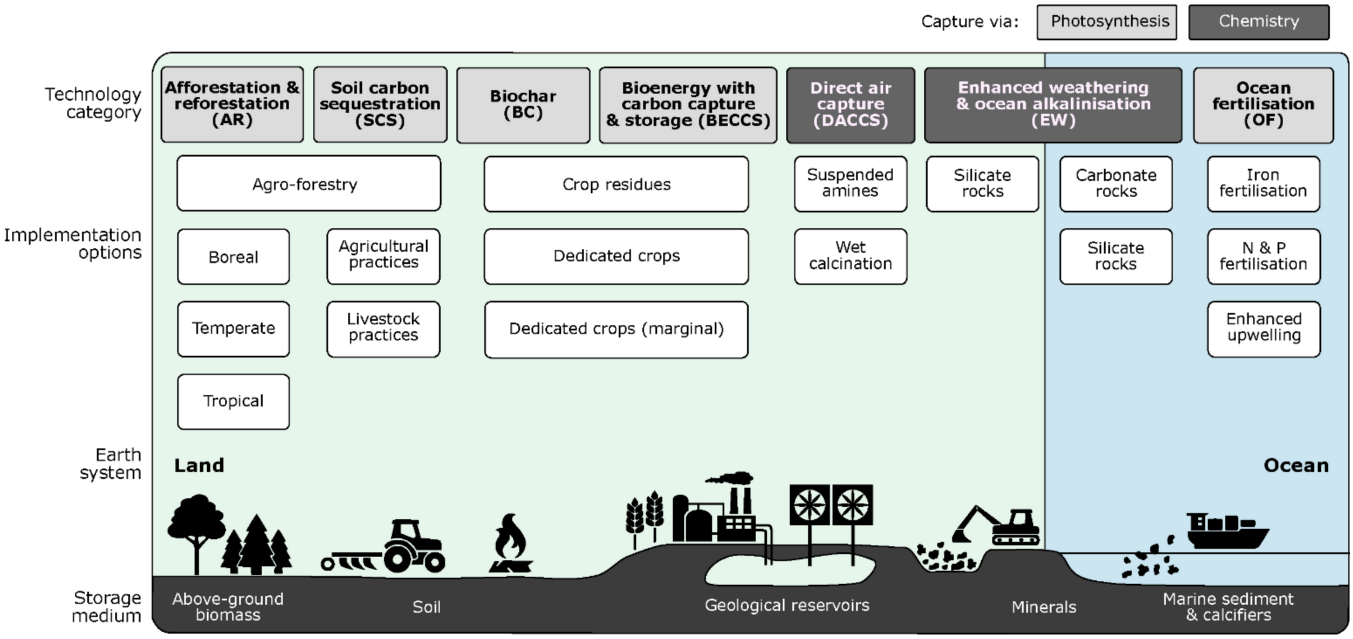


Figure 2: Non-exhaustive illustration of the current portfolio of GGRs, noting that this is a rapidly evolving area. Image reproduced from Minx et al.6

Development of UK greenhouse gas removal (GGR) policy

The portfolio of GGR methods is rapidly evolving, however most engineering-based approaches are at an early stage of commercial development and have not yet been deployed at scale in the UK. In parallel to the nature-based GGR methods being rolled out in the UK, HMG is supporting innovation and commercial development of more nascent technologies. For example:

- In June 2020, the Prime Minister announced up to £100m for Direct Air Capture Research & Development. In November 2020, we launched Phase 1 of the Direct Air Capture and other GGR Innovation Programme, which seeks to pilot feasible GGR approaches at scale as well as better our understanding of governance and ethics of GGRs.
- HMG are progressing work on developing Carbon Capture, Usage and Storage (CCUS) infrastructure that will be essential for the deployment of BECCS and DACCS. This

[6] Minx et al, Environ. Res. Lett., 2018

includes a £1 billion commitment to develop four CCUS clusters by 2030, with the first two in the mid-2020s.

HMG is also exploring the longer-term policy support that could be needed to enable a market for GGRs and accelerate the development and deployment of less mature technologies. In February 2021, we closed a joint BEIS and HMT Call for Evidence, which sought views on policy interventions that could accelerate investment in GGRs.

- Chapter 1 sought views on the role and mix of GGRs in the delivery of net zero.
- Chapter 2 invited views on policy options to catalyse GGR deployment.
- Chapter 3 covered the monitoring, reporting and verification of negative emissions.

The need for an approach to monitoring, reporting and verification (MRV)

The permanent removal of greenhouse gas (GHG) from the atmosphere is key to reaching net zero. For a GGR approach to be credibly 'net-negative' it must permanently remove more GHG from the atmosphere than it creates.

For some GGR approaches, the amount of carbon captured and stored can be easily measured and may not require periodic monitoring. In others, establishing this with necessary certainty and verifying that it remains secure will be more challenging. Both biological storage (e.g., soil or trees) and geological storage (e.g., sub-surface geological formations) are recognised as potential pathways for CO2 removal. However, they vary significantly in terms of permanence of store, associated risk of reversal, and ability to monitor which comprises accuracy and precision of monitoring, the cost and frequency of monitoring to verify quantity of CO2 stored.

To deploy GGRs on a commercial basis, in either voluntary markets[7] or as part of a compliance-based approach, it will be vital to understand:

- How much CO2 has been removed from the atmosphere,
- When that removal has taken place,
- At what rate that removal will persist, and for how long,
- In what type of sink it has been stored,
- The characterisation and durability of that store, and

[7] We are aware of the work underway to scale a voluntary carbon market, namely that of the Taskforce on Scaling Voluntary Carbon Markets (TSVCM). The TSVCM is a private sector-led initiative, initiated by Mark Carney, UN Special Envoy for Climate Action and Finance, with the goal to scale transparent, verifiable and robust voluntary carbon market to help meet the goals of the Paris Agreement. One of the TSVCM's objectives is to create a market for high-quality carbon credits, as the existing voluntary carbon market does not operate effectively due to difficulties (both real and perceived) in quality and integrity of the credits. To support this objective, they have proposed an assessment framework for credit issuers, requiring MRV to be calculated in a conservative and transparent manner, based on accurate measurements and quantification methods, and validated/verified by an accredited, third-party entity. They suggest that a future governance body will refine this proposal and take it to the next level of detail.

- The point at which a given store reaches maximum stability/saturation.

To ensure the credibility of a removal, and support market legitimacy and perception, it is also important to consider:

- Additionality – proving the removal activity is additional to what was happening anyway, in the absence of the GGR intervention,
- Avoiding double counting – ensuring geographical accountability and accuracy, so that a removal is not credited or accounted for twice.
- In achieving these aims, it will be necessary to establish an independent regulatory body who can fully and transparently audit the MRV process.
- Importantly, the scope of this report exclusively focuses on the MRV aspect of GGRs. Explicitly out of scope is any discussion on the relative costs or co-benefits of GGR pathways.

The suite of methods for assessing these requirements is known as "monitoring, reporting, and verification" (MRV), and is on the critical path to the commercial deployment of GGR.

MRV is important from both a carbon accounting and a CO2 liability perspective. The process of removing residual emissions is a one-way, permanent transfer of carbon liability from the "emitter" to the "remover", with an associated payment structure. It will therefore be necessary to develop the ability to rigorously audit the quantity of CO2 removed by a given GGR approach at a given time, and to robustly understand the extent to which that approach is likely to subsequently re-release stored CO2, informing the need for potential future remediation and associated cost. Whilst monitoring the CO2 store is vital as the project is ongoing, concluding this monitoring is an integral part of completing a GGR project.

The carbon accounting landscape

United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines, which are based on 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines, determine how GHGs can be included in national emissions accounts. However, accounting for GGR presents several challenges beyond those currently faced in emissions accounting. The technological immaturity of various GGR options means that accounting principles are not yet well established, and several wider challenges also exist:

- Permanence: GGR techniques vary in the permanence of the CO2 stored and the risk of reversal. There are no established frameworks which value the length of storage.
- Monitoring, reporting, and verification: Apart from geologically sequestered CO2, there are no accepted MRV protocols for GGR. The complexity and duration of GGR MRV will likely vary by approach and the establishment of an independent third party may well be key to carbon accounting efforts.

- International supply chains: Accounting for emissions associated with international supply chains presents a challenge for existing emissions accounting and remains subject of extensive negotiation.

Whilst current accounting and reporting guidelines provide a useful starting point for the development of an approach to MRV, further work is required to ensure these challenges are addressed.

Task and Finish Group Output

The following topics emerged as key discussion points and were explored in detail, via a combination of desk research, meetings of the Group and in stakeholder one-to-ones.

This section:

1. Summarises the key considerations in developing an approach to MRV,
2. Sets out key general principles that should be followed, and
3. Includes working assumptions of how protocols for specific GGR approaches could operate.

The issue of permanence

The permanent removal of GHGs is key to reaching net zero. Figure 3 provides an illustrative example of how leakage reduces the contribution of GGR to long term climate stabilisation and repair goals.

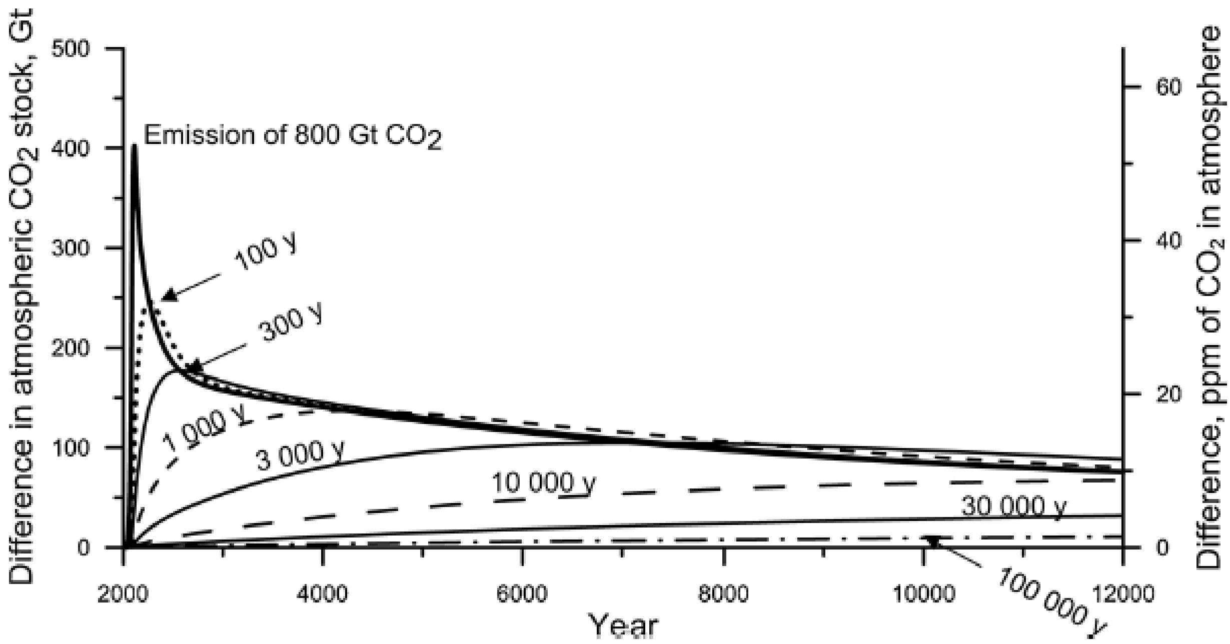


Figure 3: Impact of leakage rates relative to natural carbon cycle. As can be observed, temporary storage of 100 years has the effect of reducing atmospheric carbon stock by 39%, whereas storing CO2 for 1,000 years has the effect of reducing climate impacts by 66%. From this analysis, it emerges that one needs confidence that the level of permanence is on the order of 10’s to 100’s of thousands of years to effectively “offset” the original release. This figure was taken from the work of Lyngfelt et al.8

[8] Lyngfelt, A., Johansson, D. J. A., Lindeberg, E., (2019), Negative CO2 emissions – an analysis of the retention times required with respect to possible carbon leakage, Int J GHG Con., 87, 27 - 33

Figure 3 shows that GGR approaches which result in the leakage of CO2 after one century have the net effect of a 39% reduction relative to no GGR. After 1,000 years, this increases to 66%, and so on. On this basis, a permanent GGR can be considered inherently more valuable from a climate repair perspective than a non-permanent option.

Valuing permanence

Whilst there is currently no clear definition for a negative emissions credit, a tonne of CO2 permanently removed could, for example, be awarded one full credit. To address the issue of leakage or reversal, the concept of a partial or discounted credit could be introduced[9]. Based on Figure 3 above, a GGR approach that resulted in the leakage of CO2 after a century could be awarded, at most, 39% of a credit.

Determining the exact value of credit to be assigned to a given GGR approach is outside the scope of this report, but it should be a prerequisite to commercial demonstration of GGRs and their inclusion in carbon budgets.

Taxonomy

GGRs will be integral to both global efforts to meet the goals of the Paris Agreement and the UK-specific 2050 net zero emissions target. As the economy transitions towards net zero, GGRs will exclusively be deployed to indirectly mitigate residual emissions from hard to abate sectors of the economy. Once net zero targets are achieved, GGRs may still have a function to address residual emissions but will increasingly be deployed to deliver genuine removals. This is illustrated in Figure 4 below.

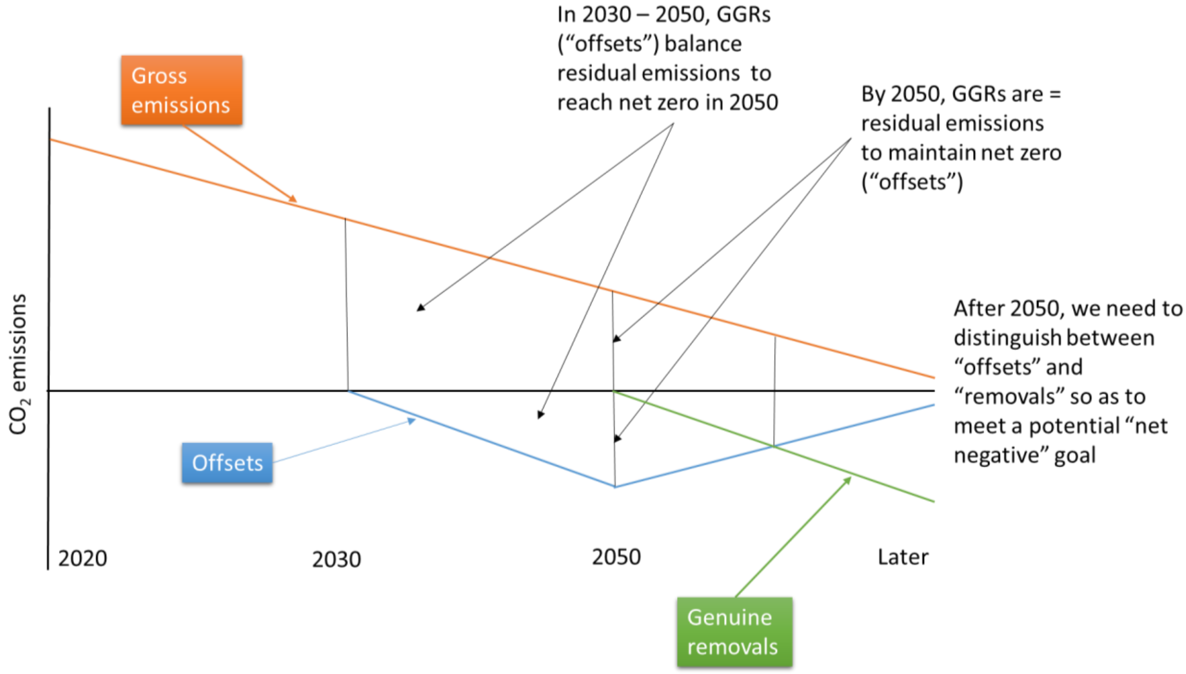


Figure 4: Illustration of the role of GGRs in the period to, and after, 2050.

[9] Haszeldine, S., et al, "Perceptions of Permanence in CO2 storage What is a long time?" Energy Transition; Geological Society, London 7 June, 2021

If, for example, CO_2 is removed from the atmosphere in 2030 via a mechanism that is understood to store CO_2 in a non-permanent sink, and this store unexpectedly reverses, e.g., re-releases the CO_2 to the atmosphere in, for example, 2060, this CO_2 will need to once again be removed from the atmosphere. Given that this will not be a “new emission”, but rather a delayed emission, understanding with whom the liability sits for this “delayed emission” will be key, as will the ability to trace back and enforce the liability against the relevant emitter. If, for example, liability is considered to revert to the original 2030 emitter, how might they be held responsible? Conversely, if the liability is considered to sit with a 2060 emitter, the same questions arise, noting that this may significantly impact the price at which the original removal service was provided. Further work is required to better understand both the level of permanence that might be associated with a given store, and also the probability of an early release owing to, e.g., fire.

Let us take the example of equivalent initial units of GGR delivered by afforestation (AF) and direct air carbon capture and storage (DACCS). The initial cost of the DACCS GGR may well far exceed the initial cost of the AF. However, the DACCS pathway will deliver permanent removal, and once the sequestered CO_2 has been securely stored, the physics of the store act to render the subsequent leakage of that CO_2 highly improbable. Conversely, the CO_2 that has been removed via the AF pathway is inherently susceptible to leakage via a variety of mechanisms, including fire, pests, or disease. Following from the example set out in Figure 3, above, a non-permanent GGR which was originally anticipated to provide 100 years of carbon storage unexpectedly reverses, for example owing to fire. In this eventuality, it will be necessary to promptly remove any leaked CO_2 – possibly via BECCS or DACCS – so as to avoid any additional climate damage. If this future cost is incorporated into the initial cost of the AF-based GGR, this may be expected to impact the price at which AF, or any other non-permanent GGR pathway, maybe provided.

Carbon avoided, carbon neutrality, and carbon removed

It is important to distinguish between avoided and removed emissions, providing clear and concise definitions of GGR. The Zero Emissions Platform (ZEP)[10] set out the following principles, which are adopted here:

1. Carbon dioxide is physically removed from the atmosphere.
2. The removed carbon dioxide is stored out of the atmosphere in a manner intended to be permanent.
3. Upstream and downstream greenhouse gas emissions, associated with the removal and storage process, are comprehensively estimated and included in the emission balance.
4. The total quantity of atmospheric CO_2 removed and permanently stored is greater than the total quantity of CO_2 emitted to the atmosphere.

For a project to constitute GGR, all four principles must be adhered to. Some examples of what do, and do not, constitute GGR are illustrated below, including certain processes which comply

[10] ZEP, “Europe needs a definition of carbon dioxide removal”, July, 2020

with Principle 1 (CO2 is removed from the atmosphere), and Principle 2 (CO2 is stored permanently) and some which do not.

In the real world, processes which have the potential for GGR will be dependent on the thorough evaluation of Principle 3 (upstream and downstream emissions) and Principle 4 (more CO2 is removed than is emitted in the entire process).

An example of GGR adhering to both Principles 1 and 2 is illustrated in

Figure 5 below i.e., CO2 is removed from the atmosphere via photosynthesis and incorporated into biomass, and once the biomass is converted for the provision of an energy service, the resulting CO2 is captured and geologically stored.

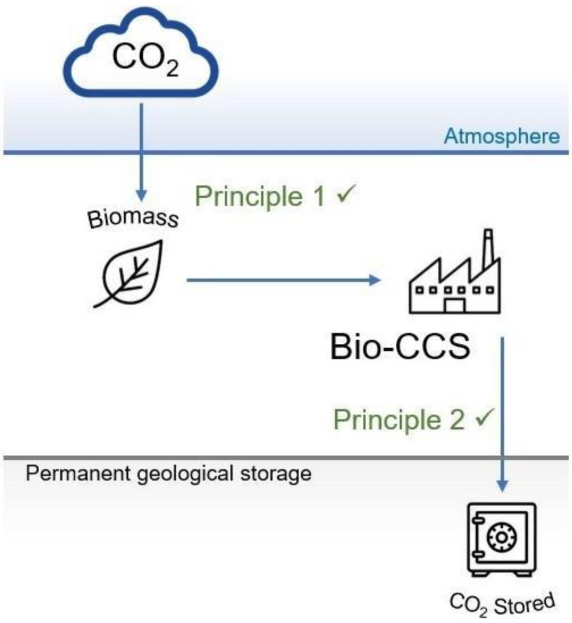


Figure 5: has the potential to result in Carbon Dioxide Removal, however a further assessment of upstream and downstream emissions is necessary. This figure has been reproduced from ZEP11. The same thinking can be applied to, e.g., direct air capture, enhanced weathering, biochar, afforestation, and so forth. Note that this example does not include Principles 3 and 4, which would also need to be considered.

However, to ensure that this approach delivers a net greenhouse gas removal, a comprehensive lifecycle analysis of the entire supply chain would need to be undertaken,

[11] ZEP, "Europe needs a definition of carbon dioxide removal", July, 2020

enabling the quantification of net removals, with due regard for storage duration. The CO2 in the geological store would also need to be monitored to ensure its security and permanence. It will be necessary to perform a similar exercise for other GGR approaches, e.g., direct air capture, enhanced weathering, biochar, etc.

It is also important to avoid conflation between “carbon neutrality” and “avoided carbon”. Carbon neutrality is illustrated in Figure 6. Here, atmospheric CO2 is recovered and used as a feedstock to produce aviation fuels. This process can be, at best, carbon neutral, and needs thorough life cycle analysis and systems evaluation to demonstrate this.

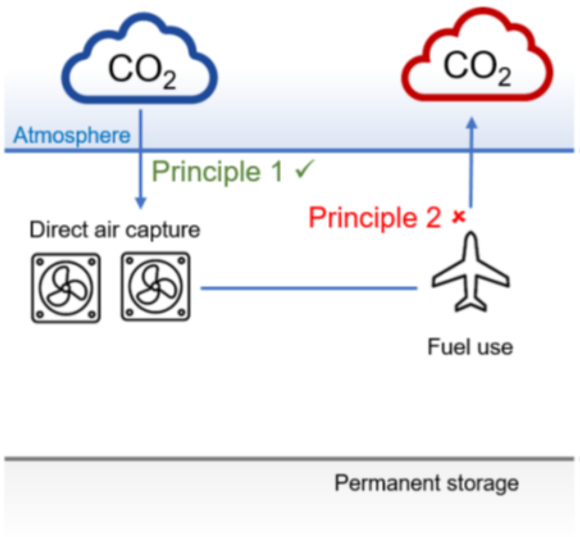
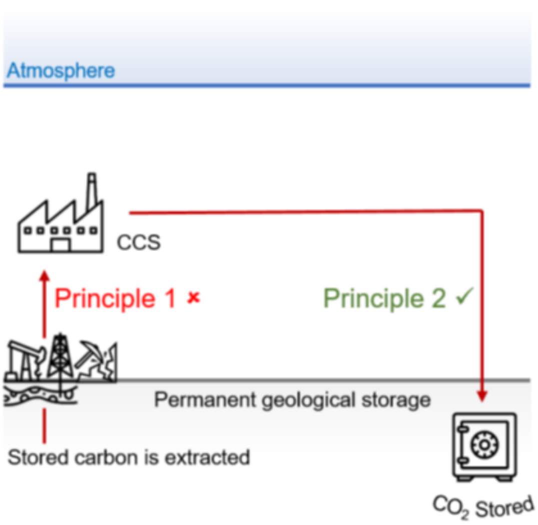


Figure 6: An example of a carbon neutral process - CO2 is removed from the atmosphere but is then incorporated into a product which quickly re-releases the CO2 to atmosphere. This process is CO2 neutral, and possibly results in avoided CO2, though this result may be challenging to demonstrate in practice. This figure has been reproduced from ZEP[12].

Figure 7 illustrates an example of an “avoided carbon” process. Here, fossil fuels are extracted and converted to provide an energy service, with the resulting CO2 captured and geologically stored. Subject to a lifecycle analysis, this approach can result in avoided CO2 emissions, but is unlikely to ever reach carbon neutrality without changing fuel type and can never result in carbon removal.



[12] ZEP, “[Europe needs a definition of carbon dioxide removal]”, July, 2020

Figure 7: An example of an emissions avoidance process. Here, fossil carbon is extracted in the form of fossil fuels, which are then converted to deliver an energy service, and the resulting CO2 captured and geologically sequestered. Again, subject to an LCA, this approach can result in avoiding CO2 emissions, but is unlikely to ever be carbon neutral and does not correspond to removed, or offset, CO2. This figure has been reproduced from ZEP.

General principles for an approach to MRV

In order to deliver a commercially viable GGR project, it is necessary to determine a beginning and end to that project. This means we must be able to accurately define:

1. When CO2 removal starts,
2. How much CO2 gets removed, at what rate, and for how long,
3. When the project gets completed.

The first two points are key to quantifying the revenue a GGR project developer can receive, and the final point is required to identify a limit on a developer's liability for a CO2 store, and the payment of any delayed revenues.

Individual MRV protocols will inherently be GGR specific, for example, the MRV approach for BECCS will be distinct to that for biochar. It is also likely that MRV for a certain approach, e.g., enhanced weathering, protocols may vary as dependent on the supplier - what might be expected of a small-scale farmer could differ to what might be expected of a major mining company. However, a generic MRV approach would entail the following steps:

1. Thorough up- and down-stream lifecycle analysis to identify, and quantify, potential sources of carbon leakage across the GGR value chain.
2. Baselining background carbon/carbon dioxide levels – this will necessarily vary depending on the GGR approach employed.
3. Developing project completion and abandonment protocols and MRV plan (to be potentially revised and updated as the project progresses).

Importantly, the development of an MRV protocol for a given project will an integral element of the development process for any GGR project. MRV will commence at the beginning of the project, and will conclude only once the project has been completed. MRV protocols will need to be continually revised and updated and all data produced as part of this process will need to be stored in a long-term auditable way.

Specific MRV approaches

The following are current working assumptions of how MRV protocols for GGR could operate.

BECCS and DACCS

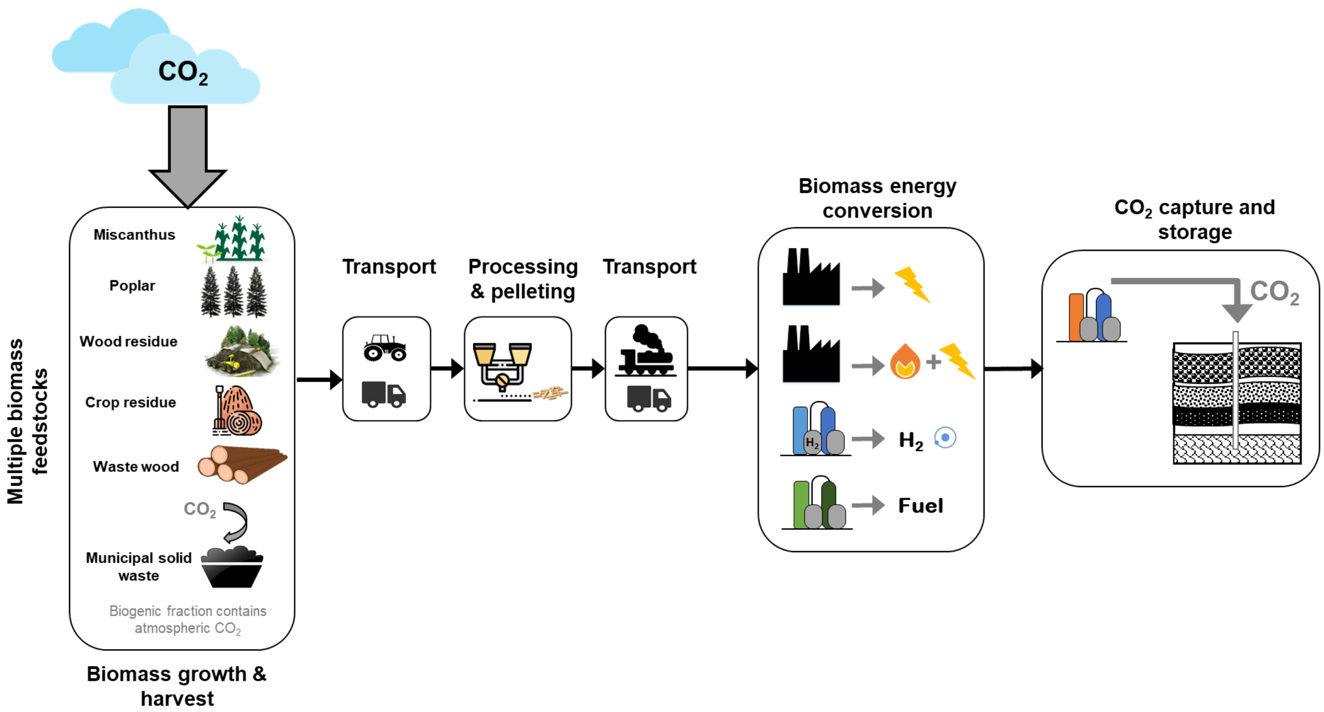


Figure 8: Illustrative flow diagram of an archetypal bioenergy with CO2 capture and storage (BECCS) value chain. The initial cultivation and growth of the biomass absorbs CO2 from the atmosphere. It is recognised that waste-derived biomass is also a potential feedstock. This biomass is subsequently harvested, processed into a fuel-grade material, and transported to a BECCS facility. The biomass can be converted via a range of processes to produce heat, power, transport fuels, or hydrogen. The resulting CO2 is then captured and transported to a geological store.

BECCS and DACCS are similar in that the captured CO2 is geologically sequestered in both cases. Both BECCS and DACCS are susceptible to upstream carbon leakage, primarily associated with the cultivation, harvesting, processing, and transport of biomass in the context of BECCS, and with the provision of heat and power in the context of DACCS. The integrity of the CO2 store can be expected to be robustly demonstrated via store appraisal, and thereafter, leakage from the store can be treated as zero. On injection, the CO2 plume can be monitored via a combination of 3D seismic surveys, seabed gravimetric monitoring, and mathematical modelling[13]. Once the CO2 plume is observed to be moving in line with model predictions, efforts towards project completion can begin. An ISO standard[14] for geological CO2 storage has already been developed and may be relevant in future geological CO2 sequestration

[13] Chadwick A., Arts R., Eiken O., Williamson P., Williams G. (2006) GEOPHYSICAL MONITORING OF THE CO2 PLUME AT SLEIPNER, NORTH SEA. In: Lombardi S., Altunina L., Beaubien S. (eds) Advances in the Geological Storage of Carbon Dioxide. Nato Science Series: IV: Earth and Environmental Sciences, vol 65. Springer, Dordrecht.

[14] ISO standard 27914:2017 for “Carbon dioxide capture, transportation and geological storage — Geological storage”.

projects. It will also be necessary to ensure that all data are stored in a long-term auditable way.

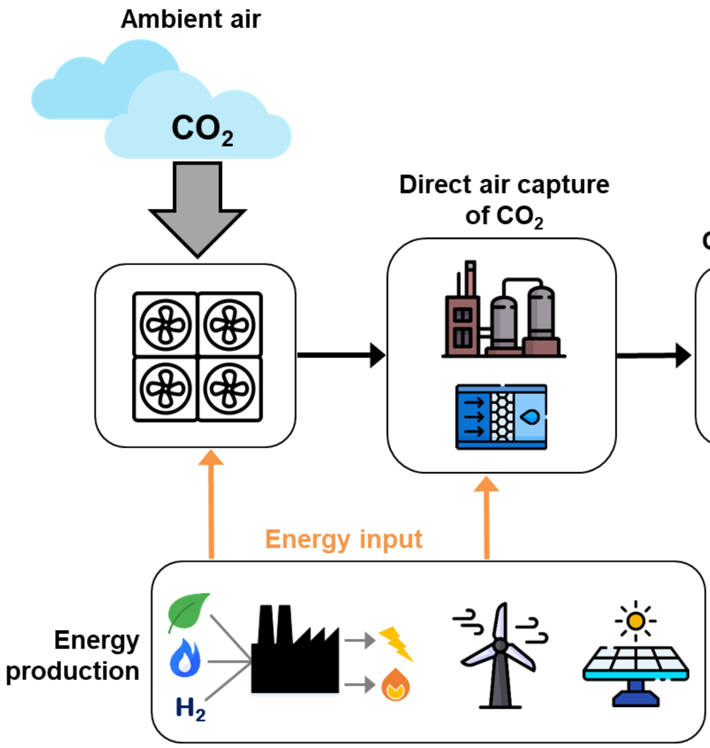


Figure 9: Illustrative flow diagram of an archetypal direct air carbon capture and storage (DACCS) value chain. Here the CO2 is directly removed from ambient air, and subsequently transported to a geological storage facility.

An illustrative calculation of carbon removal efficiency for a BECCS project is presented in

Figure below. Whilst drying of biomass is an important source of leakage, there is no one dominant source. In practice, representative carbon removal efficiencies for BECCS are anticipated to be between 65 – 85%, as a function of CO2 capture rate, supply chain, and power plant efficiency.

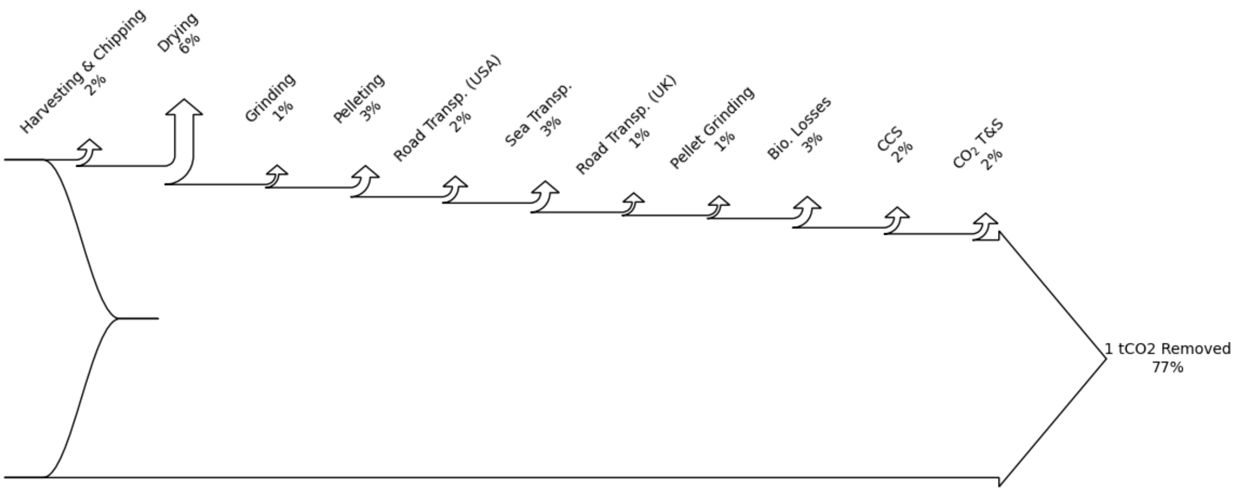
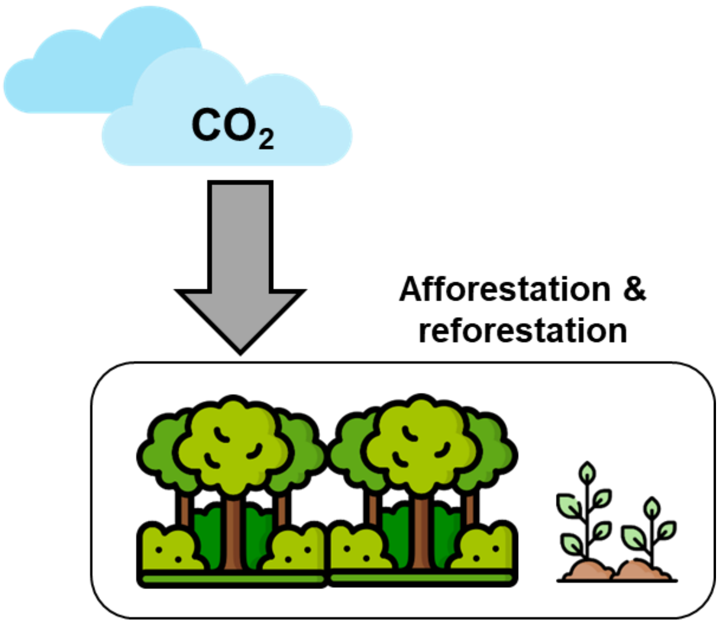


Figure 10: Illustrative carbon removal efficiency diagram for a UK BECCS project using biomass imported from the USA. This example assumes 98% CO2 capture. At 90% capture rate, the carbon removal efficiency is reduced to approximately 70%.

The sample calculation shown here assumes a 98% CO2 capture rate[15], and the overall removal efficiency is reduced to approximately 70% if a 90% capture rate is used. Beyond that, many of the key sources of carbon leakage in BECCS can be expected to reduce in line with the decarbonisation of the broader energy system.

In the context of direct air carbon capture and storage, the potential for carbon leakage is primarily related to the carbon intensity of the energy (heat and power) used to operate the process.

Afforestation/reforestation



[15] Feron, P., et al., (2019), Towards Zero Emissions from Fossil Fuel Power Stations, Int J GHG Con., 87, 188-202

Figure 11: Illustration of afforestation and reforestation. At its core, this is the establishment, restoration, and active management of forests to create and preserve a carbon sink. Importantly, in order to materially contribute to greenhouse gas removal, the forests thus established must be maintained in perpetuity, and any leakage promptly addressed via the direct removal.

Afforestation is the process of planting trees, to establish a forest or stand of trees in an area where there was previously no tree cover. Reforestation involves replanting an area with trees. By absorbing CO2, forests are an example of a nature-based approach to reducing the amount of carbon in the atmosphere. It is recognised that afforestation and reforestation provide a range ecosystem and environmental co-benefits in addition to contributing to carbon management. Addressing these co-benefits is out of scope for this report.

It takes forests some time to reach their maximum sequestration rate, varying as a function of species, climate, and forest management practices. Depending on the species, the trees will reach maturity after around 20 to 100 years, then saturating in terms of CO2 removal, after which they no longer result in net GGR. However, additional gains can be made through forest management, such as by optimising thinning and improved rotation. With appropriate management, carbon can be stored in forests indefinitely, but the permanence of this storage could be compromised by resumption of deforestation, or by natural disturbances such as fire, disease, or drought.

Whilst there are complexities of MRV in the land sector, an approach would include calculating the baseline carbon stock at the start of a project by reference to maps, photographs, remotely sensed images or filed survey results, which confirm the condition of the vegetation and soil before forest establishment.

If likely to be significant (e.g., ≥ 5% of the project carbon sequestration over the duration of the project), projects would need to calculate how carbon stocks on the site would have changed over the project duration had the project not gone ahead. The baseline scenario is conservative by accounting for sequestration but not emissions, meaning the net carbon sequestration (project sequestration minus baseline) will not be more than the actual sequestration of the ecosystem.

There should also be a clear plan for each project on how the forest will be managed to minimise CO2 losses. This should include a risk assessment to ensure against unforeseen losses.

Periodic review and verification of projects at defined intervals will be required, e.g., at year five initially and then at least every 10 years. They should be monitored for 6-12 months prior to each verification date and will need to have a monitoring plan in place.[16]

[16] Approach adapted from standard and guidance of the Woodland Carbon Code

Enhanced Weathering

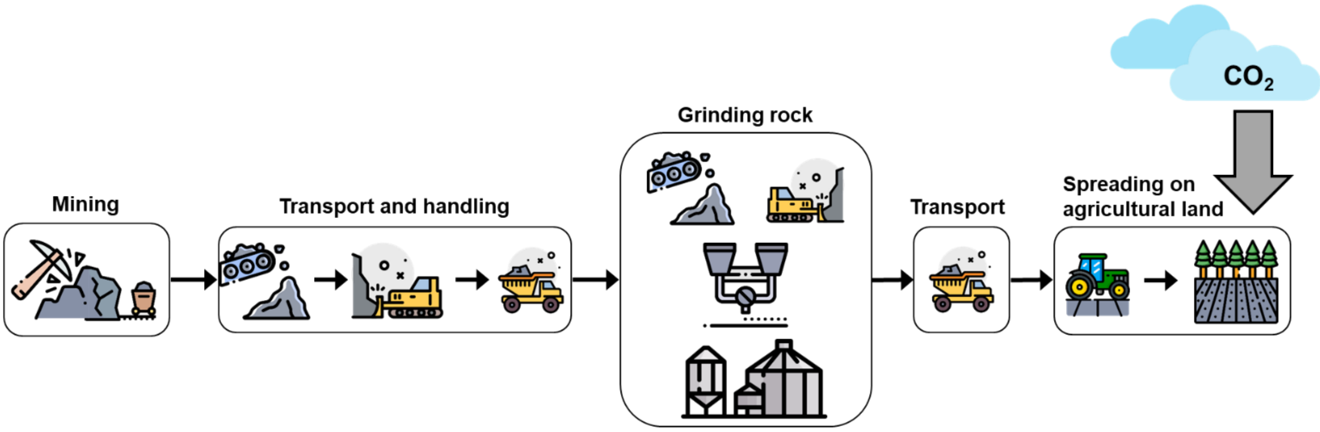


Figure 12: Illustrative flow diagram of an archetypal enhanced weathering (EW) value chain. Here, carbonate-able minerals, such as basalt or olivine, are mined, and then processed to produce a fine powder, which can be then transported and spread on available land. Subsequently, the carbonation of this material proceeds as a function of particle size, temperature, water, and time. CO2 removed in this manner can be considered to be permanently removed.

The enhanced weathering process, also referred to as accelerated weathering, is essentially contacting CO2 with silicate rocks, such as basalt, or olivine, in the presence of water. This is a naturally occurring process and is a key part of the slow carbon cycle, which sequesters atmospheric CO2 over millions of years. This process can be accelerated by pulverising the rocks to a powder, thereby increasing the available reactive area.

Enhanced weathering projects could be delivered by a range of stakeholders, including the farming community, other large landowners, or the mining industry.

There are two options for ex-situ enhanced weathering projects to proceed:

1. Passive exposure of mineral material to the atmosphere via, for example, land spreading, or a mine tailings facility.

2. Active exposure on mineral material to a "concentrated" CO2 stream in a reaction vessel, where this CO2 stream could be anything from air up to pure CO2 with obvious cost and carbon balance implications. Reaction conditions[17] are likely to be between 25 – 155C and 1 – 90 bar, with a residence time of between 30 – 14,440 minutes, corresponding to a reactor volume of between 2,120 – 795,699 m3[18].

In all cases, it will be necessary to develop a minerology baseline, which will require an understanding of the background minerology, i.e., origin, composition, etc. In addition, owing to natural heterogeneity, geostatistical sampling of the prepared material will likely be essential. Ultimately, it may be necessary to define a standard composition of mineral material to be

[17] Kirchofer, A., et al., (2012), Impact of alkalinity sources on the life-cycle energy efficiency of mineral carbonation technologies, Energy Environ. Sci., 5, 8631
[18] For reference, an Olympic swimming pool is ~ 2,500 m3

distributed and spread on land to reduce barriers to longer term monitoring. As the carbonation reaction progresses, periodic sampling of the reacted material is likely to be required. In an active exposure context, a mass balance on the CO2 stream will also be important to reconcile these figures and close the overall mass balance. In a passive exposure context, a CO2 balance will not be feasible, and it may be necessary to rely more completely on sampling of carbonated material. Finally, data will need to be stored in a long-term auditable way. An illustrative carbon removal efficiency calculation for a passive enhanced weathering process is presented in Figure 13 below.

As illustrated here, the carbon removal efficiency of a passive enhanced weathering project is around 65%. Primary sources of carbon leakage are the pulverising of the mineral material and the transport. Importantly, these might be expected to considerably reduce in line with broader decarbonisation of the energy system.

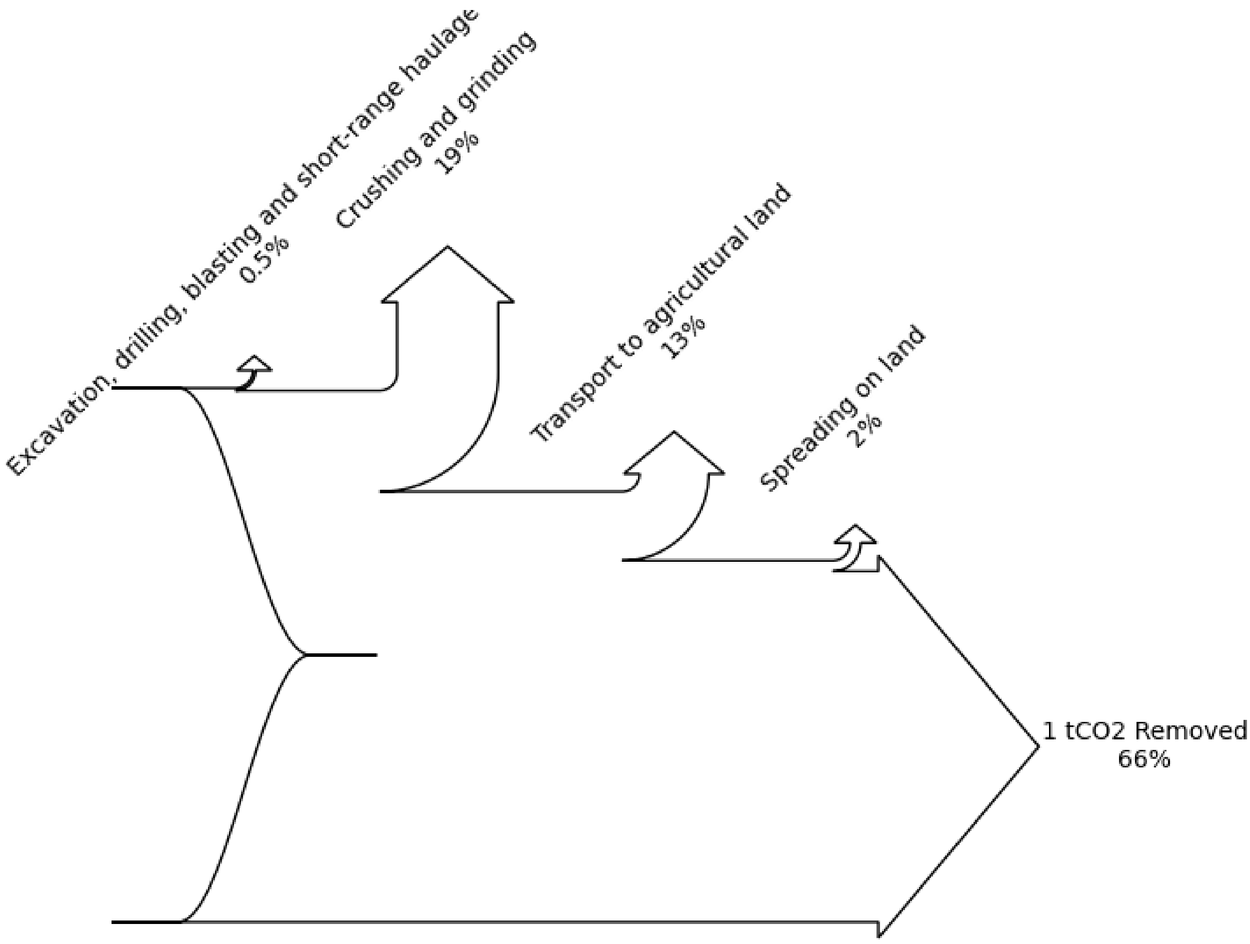


Figure 13: Illustrative carbon efficiency of passive enhanced weathering process. Here it is assumed that the mineral material is available in the UK. It can be observed that the primary sources of carbon leakage are the energy required for mineral size reduction, transport, and spreading on land.

Biochar

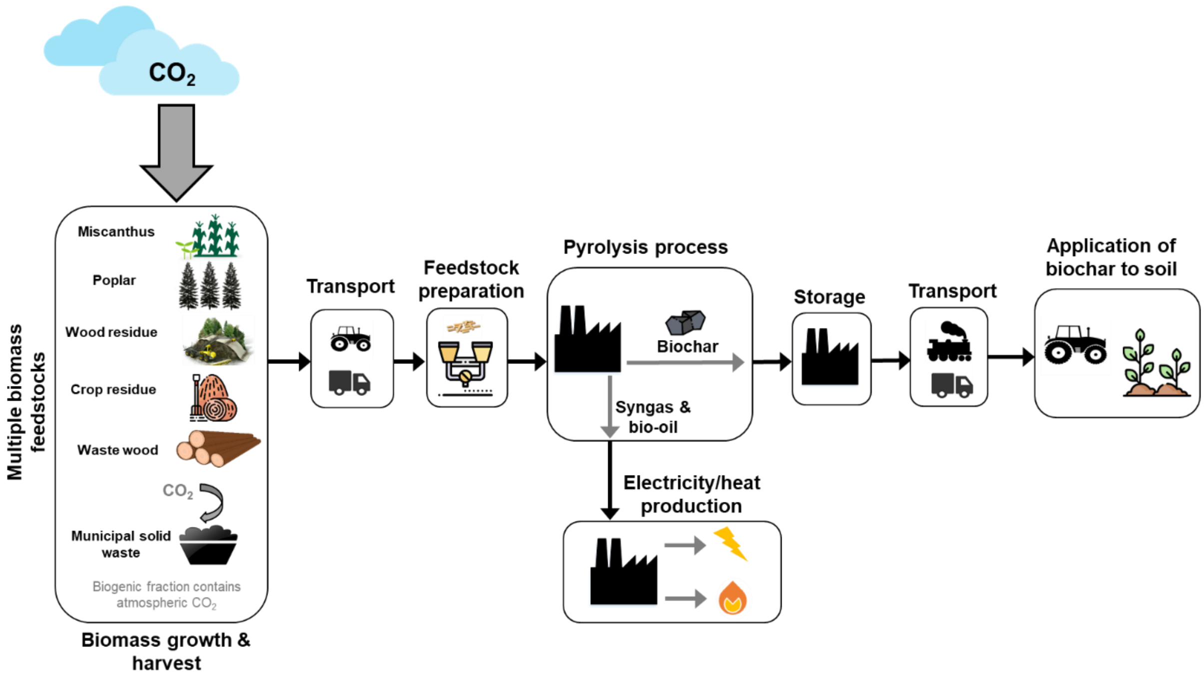


Figure 14: Illustrative flow diagram of an archetypal biochar value chain. The initial cultivation and growth of the biomass absorbs CO2 from the atmosphere. The biomass is then processed and fed to a pyrolysis process, which produces both biochar and a range of co-products, which can be used for the provision of energy services. The biochar is then subsequently incorporated with the soil where it decays over time as a function of the pyrolysis process conditions and prevailing soil conditions.

The biochar production process is quite well understood. However, there are many ways of making biochar, with more durable chars requiring higher temperatures, making them more costly. Similarly, “fast” and “slow” pyrolysis processes result in more/less biocarbon being retained in the char. Once the initial oxidisation has taken place, the remaining char is quite stable, with 60 – 70% biocarbon in the char is retained in the soil for centuries or more. However, the addition of char has the potential to increase microbial activity and produce CO2, thus potentially reducing the overall carbon removed by this GGR pathway.

Similarly to BECCS, biochar incorporates a biomass supply chain, which will need to be carefully and comprehensively lifecycle analysed to understand its carbon intensity. Moreover, approximately 50% of the biocarbon is lost from the biochar via the pyrolysis process[19], representing a critical element of biochar’s carbon value chain.

Thereafter, further carbon leakage will be associated with the application and incorporation of biochar into a given tract of land. Understanding the propensity for carbon leakage arising from the application of char is likely to require comprehensive baseline measurement of soil composition in terms of soil quality and carbon content.

[19] Woolf, D., Amonette, J., Street-Perrott, F. et al. Sustainable biochar to mitigate global climate change . Nat Commun 1, 56 (2010).

Owing to the inherent heterogeneity of land, multiple samples from an area are likely to be required to develop an accurate description, with precise number and function of the level of heterogeneity of the land. Importantly, whilst there is ample scope for innovation in this context, laboratories already exist for this kind of analysis, with soil samples routinely collected for nitrogen, phosphorus and potassium (NPK) analysis, thus the level of additional burden in this area appears low.

Following char application, a period during which the labile material decays ensues. However, biochar is highly heterogeneous, and comprises condensed and residual aliphatic compounds and black carbon, with each of these compounds having different decay kinetics in soils. Biochar decay can be characterised by a “rapid decay” phase, and a “slow decay” phase[20],[21].

The details of each phase will vary as a function of soil composition and biomass type. Understanding of these processes is emerging, with substantial uncertainty remaining; therefore, between baselining measurement, ongoing monitoring, and additional post-application monitoring required to demonstrate stability, biochar might require as much as 20 years of MRV commitment, if not substantially more.

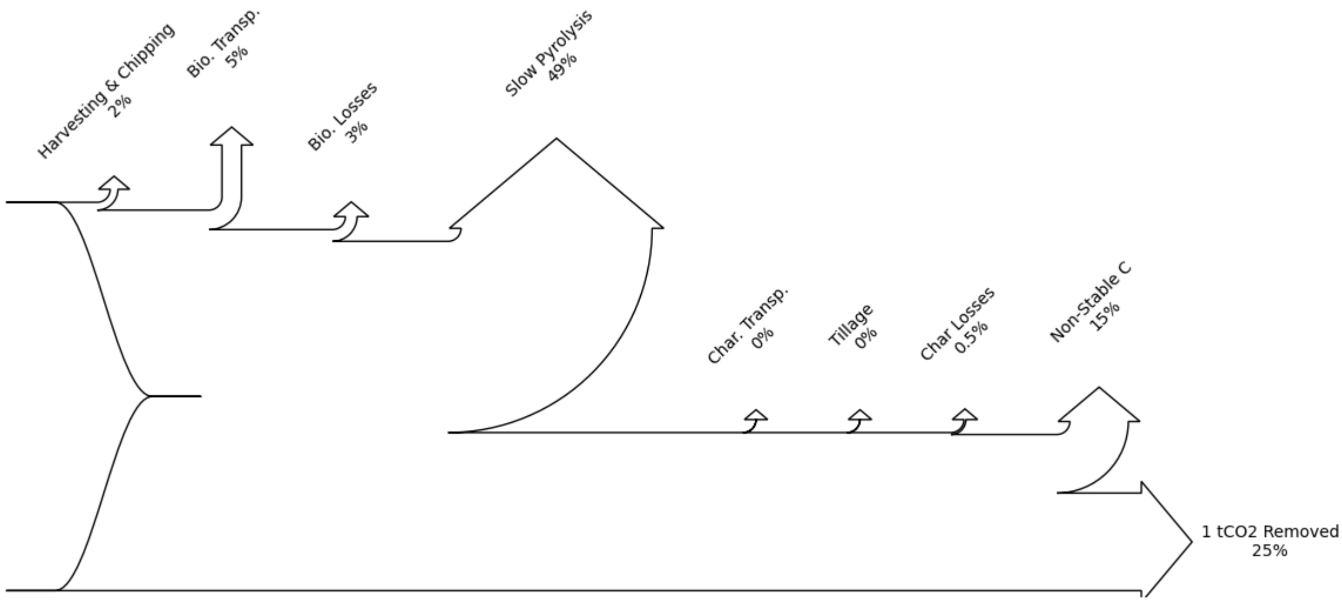


Figure 15: Illustrative carbon removal efficiency diagram for biochar application in the UK using forest residue from Scotland with char application in the midlands.

The carbon removal of biochar might be expected to be in the order of 25%, with significant carbon leakage occurring during the pyrolysis process and the post-application decay of labile carbon. As these primary losses are inherent to pyrolysis technology and the non-durable nature of the labile portion of biochar, this leakage is not anticipated to meaningfully decline in line with broader decarbonisation efforts.

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20 Kuzyakov, Y., Subbotina, I., Chen, H., Bogomolova, I. & Xu, X. Black carbon decomposition and incorporation into soil microbial biomass estimated by 14C labeling. Soil Biol. Biochem. 41, 210-219 (2009).

21 Cowie, A. & Singh, B. Decomposition rate of biochar in soil - an important factor affecting the greenhouse gas balance. IBI conference 2008 (2008).at http://www.biochar-international.org/images/Cowie_poster_IBI_Newcastle.pdf

Future work

The advice and input of the Task and Finish Group members, and other key stakeholders, has helped to inform the future work necessary to progress the development of an MRV policy for negative emissions, to support the further development and commercialisation of GGRs.

To deliver a commercially viable GGR project, it is necessary to determine a beginning and end of that project, meaning that we must be able to accurately define:

3. When CO2 removal starts,
4. How much CO2 gets removed, at what rate, and for how long,
5. When the project gets completed.

The first two points are key to quantifying the revenue a GGR project developer can command, and the final point is required to identify a limit on a developer's liability for a given CO2 store.

Given the importance of the permanence and effective storage of CO2, it will also be essential to develop an approach to valuing GGRs (or removal credits) relevant to the permanence of the store.

> Agree on a level of removal credit as a function of permanence.

Detailed MRV protocols

We have identified that an MRV protocol might be expected to entail the following steps:

6. Thorough up- and down-stream lifecycle analysis to identify, and quantify, potential sources of carbon leakage across the GGR value chain.
7. Baselining background carbon/carbon dioxide levels – this will necessarily vary depending on GGR approach employed.
8. Developing of project completion and abandonment protocol and MRV plan (to be potentially revised and updated as project progresses).

However, the details of MRV protocols will be GGR-specific and will need to be continually revised and updated, in line with increasing project experience and an improved science base.

> Establish and address gaps in the science in MRV capabilities for each GGR approach.
>
> Develop detailed MRV protocols for each GGR approach, in parallel with initial commercial demonstration.

Independent regulatory function

Given the recognised importance of GGR, we need to put in place an independent monitoring, reporting and verification regime to ensure that the amount and permanence of removals are quantified, robustly and transparently, with tolerable uncertainty. It will therefore be essential to establish an independent function for GGRs, with the competence to provide MRV services to GGR projects and communicate this information to HMG. This organisation would have the key role of auditing removed CO2, determining when a CO2 store had reached maximum stability, and advising when MRV might be concluded.

Given the role of GGRs in the sixth[22] UK carbon budget, with anticipated deployment of GGR in the UK by 2030, establishing this function in the near term should be a priority.

Establish an independent function to sit between project developers and HMG and be responsible for an independent MRV regime, to ensure that the amount and permanence of removals are quantified, robustly and transparently.

Ensuring international alignment

Accounting for emissions associated with international supply chains presents a challenge for existing emissions accounting and has been the subject of extensive negotiation. The deployment of GGR is an inherently international challenge and will present additional complications. Supply chains of key raw materials, from biomass to carbonatable minerals will potentially be international in nature. It is also highly likely that "GGR as a service" will emerge as core to meeting climate targets in the longer term[23],[24] , therefore ensuring that approaches are internationally aligned will be key to ensuring no double-counting between different schemes, sectors, nations or accounting systems.

Engage with relevant international stakeholders to share knowledge and understanding, and collaborate on addressing the governance and accounting challenges relevant to GGR. Global companies should also be asked to align their operations on a multi-national level.

[22] https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf
[23] C Pozo, Á Galán-Martín, DM Reiner, N Mac Dowell, G Guillén-Gosálbez (2020), Equity in allocating carbon dioxide removal quotas, Nature Climate Change 10, 640 - 646
[24] M Fajardy, N Mac Dowell (2020), Recognizing the Value of Collaboration in Delivering Carbon Dioxide Removal, One Earth 3 (2), 214-225

Key actions

Recommended action	Responsibility	Timeframe
Explicitly identify any gaps in the science in MRV capabilities for each GGR approach.	HMG	Within 1 – 2 years
Agree on a level of removal credit as a function of permanence. This would be a clear communication tool to enable project developers to quantify carbon removal revenue streams.	HMG	Within 1 – 2 years
Engage with relevant international stakeholders to share knowledge and understanding, and to collaborate on addressing the governance and accounting challenges relevant to GGR.	HMG	Within 1 – 2 years
Establish an independent function to sit between project developers and HMG and be responsible for a monitoring, reporting and verification regime, to ensure that the amount and permanence of removals are quantified, robustly and transparently.	HMG	Within 2 – 4 years
Develop detailed MRV protocols for all non-geological sequestration GGR approaches, including explicit provision for the prompt recovery of CO2 in the case of post-removal leakage. This should be done in parallel with initial commercial demonstration.	HMG/independent function	Within 2 – 4 years
Consider developing a regulatory framework to enable the participation of GGR in a potential Emissions Trading Scheme and in international carbon markets.	HMG	Mid- to late-2020s

Conclusions

The prompt and permanent removal of greenhouse gas emissions (GHG) is key to reaching the goals of the Paris Agreement and the UK's net zero commitments.

The existing portfolio of GGR approaches is quite diverse and will inherently vary in the way in which they deliver GHG removal. In this, there are three key variables to consider – efficiency, timeliness, and durability of CO2 removal.

It is important to distinguish between avoided and removed emissions, providing clear and concise definitions of GGR. Given the importance of the permanence and effective storage of CO2, it will also be essential to develop an approach to valuing GGRs (or removal credits) relevant to the durability of the store.

Some GGRs, like afforestation, are highly efficient at removing CO2, in that there is very limited CO2 leakage associated with a given afforestation project. However, owing to the time required for trees to grow, the timeliness of removal is relatively poor. Similarly, the durability of the established CO2 sink is a strong function of the long-term forest management strategy, in addition to force majeure, such as fires. Others, such as BECCS or DACCS can provide highly durable CO2 removal, but with the potential for CO2 leakage arising from the upstream biomass supply chain, or the carbon intensity of the energy used to operate the DACCS facility. The timeliness of BECCS can also be strongly impacted by any direct or indirect land use change associated with the project, incurring a "carbon debt" and introducing a delay to removal[25].

Similarly, removals provided by enhanced weathering enhanced weathering projects will be delivered as a function of several parameters, including particle size, whereas those delivered by biochar will decay with time. Therefore, to quantify and qualify the value of the GGR provided by a given approach, or combination of approaches, the development of detailed, robust MRV protocols for each GGR approach are vital.

In this context, MRV protocols for geological sequestration of CO2 are well established. For example, CO2 has been stored in the Norwegian context for more than 20 years as part of the Sleipner project. Similarly, forest management practices are well established, and might be readily adapted to afforestation/reforestation projects. Thus, from an MRV perspective, there is no obvious barrier to deploying these projects in the near term.

Other GGR approaches, such as enhanced weathering, soil carbon storage, or biochar, do not, as yet, have established MRV protocols, and fundamental science questions and technology challenges remain, with considerable amounts of work currently underway to address these knowledge gaps. Nevertheless, these GGRs may play a role in the UK context in the period post 2030.

[25] Fajardy and Mac Dowell, Energy & Environmental Science (2017) 10 (6), 1389-1426

Acknowledgements

Task and Finish Group members

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