CORE THE GREENHOUSE GAS REMOVAL HUB

Governing permanence of Carbon Dioxide Removal: a typology of policy measures

Policy report

November 2023

The London School of Economics and Political Science
CDRSynTra
Sponsored by the Federal Ministry of Education and Research
Grantham Research Institute on Climate Change and the Environment

About the authors

Josh Burke is a Senior Policy Fellow at the Grantham Research Institute on Climate Change and the Environment.

Dr Felix Schenuit is a Research Associate at the German Institute for International and Security Affairs (SWP) in Berlin.

Josh Burke developed the idea for the paper and drafted the paper. Felix Schenuit contributed to the drafting of Chapter 3 and revisions of the paper.

Acknowledgements

The authors would like to thank Freya Chay, Stephanie Arcusa, Mark Preston Aragones and Leo Mercer for their detailed and helpful comments on pre-publication drafts of this report. Thanks also go to Jay Shah and Felix Grey. All errors and omissions remain those of the authors. The views expressed in this report represent those of the authors and do not necessarily represent those of the host institutions or funders. This research was not commissioned by the Department for Energy Security and Net-Zero and does not reflect the views of government. The authors have no relevant financial or non-financial interests to disclose.

Josh Burke acknowledges financial support from the Grantham Foundation for the Protection of the Environment, and from CO2RE – The Greenhouse Gas Removal Hub. Felix Schenuit acknowledges financial support from the project CDRSynTra, funded by the German Federal Ministry of Education and Research (BMBF), grant number: 01LS2101A;

This paper was first published in November, 2023 by CO2RE – The Greenhouse Gas Removal Hub. CO2RE is funded by UK Research and Innovation grant reference NE/V013106/1.

Suggested citation: Burke, J and Schenuit, F. (2023) Governing permanence of Carbon Dioxide Removal: a typology of policy measures. CO2RE – The Greenhouse Gas Removal Hub.

Contents

Executive summary

Key messages

1. How long different Carbon Dioxide Removal (CDR) methods can store carbon matters fundamentally for the specific role for climate policy and the optimal governance and regulatory framework.
2. Determining what is fungible in emissions and removal accounting depends on nuanced concepts in climate science, climate economics, and real-world market practices. Fungibility should therefore not be simply cast as technocratic and value-free. It has potentially dramatic environmental and economic implications for society.
3. CO_2 (re-)emitted from non-permanent removal methods needs a continuous obligation to remove CO_2 and is not equivalent to permanent CDR. However, creating a viable business case based on responsible governance regimes for non-permanent CDR is critical as we need a diverse portfolio of CDR.
4. What appears to be 'cheap' removal in the land sector actually implies large future costs when the costs of governing impermanence are fully accounted for.
5. Emerging CDR policy risks masking a lack of real fungibility between emissions reductions and non-permanent removals.
6. Policies to govern permanence should be applied to both market based and non market based policy instruments.
7. Given the lack of substitutability between some forms of CDR and emissions reductions, not all types of CDR-based carbon credits can be traded in one harmonised carbon market. If they were integrated in one market, artificially cheap certificates from non-permanent methods could dominate the market for CDR; undermining the business case for permanent but more expensive CDR methods.
8. It is critical that fungibility measures avoid obfuscating important differences in CDR credit quality. Markets that sell CDR credits need more transparency, not less, including on the permanence of storage and sustainability implications.
9. Monitoring, Reporting, and Verification (MRV) and certification schemes are – although quite technical – an arena for political struggles over the future of specific CDR methods. Actors with stakes in CDR development and deployment are aware of the key role of MRV and accounting schemes, which is why their design will become increasingly contested.

Recommendations

1. Foundational measures (MRV) should come first in the policy sequencing and apply to all CDR regardless of differing permanence and policy/market design. As a minimum, these measures need to be refined and strengthened. Policymakers should also consider developing and regulating minimum standards for MRV.
2. Policymakers seeking to include afforestation or other non-permanent CDR within compliance carbon markets should prohibit their use and set minimum storage durability and sustainability requirements.
3. Policymakers should promote a spectrum of visible costs within policy frameworks, reflecting the diversity of carbon-removal approaches.
4. Bespoke policy frameworks for non-permanent CDR are needed to provide a different route to market. This could include subsidies for land-based removals or the integration into a separate ETS that only covers land use and agricultural emissions and removals. Non-permanent CDR can be used to balance out non-CO_2 emissions in the agricultural sector with shorter atmospheric lifetimes than fossil CO_2 emissions.

Why is Carbon Dioxide Removal needed?

Carbon dioxide removal (CDR) from the atmosphere is an inevitable component of operationalizing net-zero targets into practical climate policy. Indeed, integrated assessment model pathways that limit warming to 1.5 degrees Celsius include – in addition to deep reductions of gross greenhouse gas emissions – a massive scale up of CDR methods.

Policy context

Explicit CDR policy frameworks and implementation strategies are nascent and vary between jurisdictions. The United States for example, has announced plans for a government led procurement scheme in order to stimulate demand as well as generous subsidies for Direct Air Capture (DAC) through 45Q and the Inflation Reduction Act. The integration of CDR into existing compliance carbon markets is an alternative approach. One that has unsurprisingly gathered greater traction in the EU and the UK since large scale compliance carbon markets are already in operation (i.e. the EU and UK ETS). Which CDR methods will be integrated into future compliance markets remains an open question as there may need to be some differentiation based on permanence of storage.

However, a fundamental challenge is that emissions trading schemes (ETS) are presently designed to handle only positive emission caps and are not compatible with the target of net-zero. New allowances in the UK and EU ETS are expected to end around 2040. With a tighter cap, prices are expected to rise. Excessive CO_2 price spikes and volatility has the potential to undermine the political acceptance and support for emissions trading as a central climate policy instrument. In order to enhance liquidity and maintain their role as a cornerstone of UK and EU climate policy, emissions trading schemes must successfully evolve to include CDR and transition from a positive to a net-zero compatible emissions trading system. In part, CDR inclusion is being driven by these pressures, rather than whether the policy is a first best solution to financing the net negative economy.

CDR methods have different characteristics which limit fungibility

Despite the common feature of removing carbon dioxide, CDR methods can be very different. Implementation strategies need to reflect that different methods have very different characteristics in terms of their cost, technological maturity, storage duration, risk of reversal and additionality (i.e. that the carbon removed by a project or activity is over and above what would have happened in its absence).

For CDR units to operate efficiently within compliance carbon markets CDR units must be tradeable with fossil CO_2 emissions. In other words, heterogeneous CDR units must be considered to have equivalent value and therefore be comparable and interchangeable for the purposes of settling compliance obligations in a given carbon market.

One element inhibiting the development of these markets is the absence of an accessible and agreed upon framework for evaluating the quantitative relationship between 1 tonne CO_2 stored 'permanently' and 1 tonne CO_2 stored over a shorter time period. This policy report seeks to map the status quo and propose a typology of policy measures and bundles that can be used to help address the challenging questions on permanence and tradeability in CDR policymaking. Whilst this typology of measures has its genesis in the voluntary carbon market it is also intended to help those designing similar measures for future compliance markets too or alternative policy instruments.

"This policy report seeks to map the status quo and propose a typology of policy measures and bundles that can be used to help address the challenging questions on permanence, and tradeability in CDR policymaking."

Governing permanence

We first map different groups of measures related to efforts to govern for the permanence of different removals. In a second step, we propose a policy sequencing structure for developing credible rules in CDR policy.

Tier 1: MRV as a foundational measure

A practical starting point for any permanence accounting is Monitoring, Reporting and Verification (MRV) schemes which assess the veracity of a carbon removal claim. MRV schemes can provide assurance that removals are additional and not harmful to local environments or communities. MRV is not considered an optional measure, but MRV should apply to all removals that are integrated in accounting and market structures. The scale of the challenge should not be underestimated, both scientifically and politically.

Tier 2: Building blocks of Governing permanence

The second tier consists of more specific groups of measures, each addressing distinct governance challenges that arise from different levels of permanence. That said, the measures should not be viewed as mutually exclusive but as complimentary and interconnected. A multiplicity of combinations are possible. Each measure has equal weighting although their application will vary depending on the market structure and the CDR method.

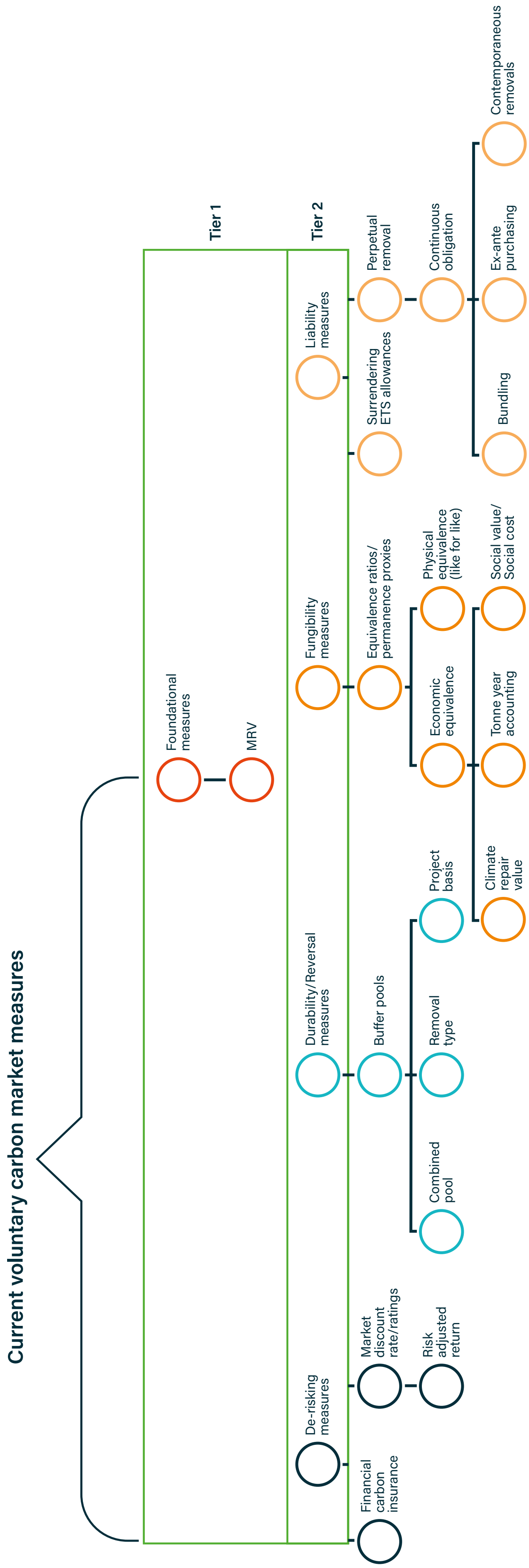

Figure ES1: Governing permanence: Typology of measures.

A brief explanation of each measure is outlined below. For more detail, please see page 20.

De-risking measures include financial carbon insurance and market discount rates/ratings agencies.

Durability measures refer to the risk that certain types of carbon removal may be more prone to reversal where carbon is re-released into the atmosphere due to extreme weather events, disease, site/facility maintenance or poor land use governance. The main measure is the use of buffer pool.

Fungibility measures attempt to quantitatively value CDR with different levels of permanence, from which equivalence ratios can be produced. Equivalence ratios describe how many tonnes of CO_2 need to be temporarily stored to account for an additional tonne of CO_2 emitted to the atmosphere today.

Liability measures refer to a set of mechanisms that stipulate the storage duration period and legally obligate companies to continually remove carbon in the event of a reversal or at the end of a project lifespan.

Policy Sequencing: A three-stage approach

As a second stage after the mapping of existing measures and for the purposes of practical CDR policymaking, we suggest a three-stage conceptual policy sequencing for addressing the five groups of measures (MRV, de-risking, durability, fungibility, liability) identified in the mapping above. Policy sequencing is a key strategy of climate policymaking and proved to be successful in overcoming political challenges in other areas of decarbonization strategies.

The first stage, as already indicated by the two tiers in the measure mapping, is to attain **credible certification** of removal activities via the foundational measure of a MRV scheme. Such a scheme is the prerequisite for any CDR policy that aims at integrating removal activities into climate policymaking.

In the second stage, a sequencing strategy to govern permanence should contain measures to **govern the risks of reversal**. The application of permanence measures is good practice for a broad range of non-market based policy instruments and will play an important role in upcoming CDR policy initiatives. For example, if governments are attempting to scale CDR via result-based subsidies or public procurement (e.g. carbon contract for difference, or feed-in-tariffs), liability arrangements and buffer pools help to govern the risk of reversal.

"The application of permanence measures is good practice for a broad range of non-market based policy instruments and will play an important role in upcoming CDR policy initiatives."

In a third stage, when CDR policy aims for the integration into market-based policy instruments such as compliance carbon markets, CDR policy will have to establish tradeability of CDR certificates and ETS allowances. This is not to imply that all CDR policymaking must adopt the suggested sequencing's third phase. CDR can be integrated into climate policy architectures without creating tradeability. However, it is a prerequisite for trading emissions and removals within the same compliance market. This can be achieved by designing a holistic policy package that combines some or all the measures in the typology, rather than just using 'fungibility measures' in isolation (see ES1).

In this context, it is crucial to exercise responsible decision-making, not just for technical matters relating to economic and physical equivalence but also for the political implications associated with these decisions. Careful consideration must be given to the issue of moral hazard, especially due to the fact that incorporation into the carbon market has the potential to impede efforts to reduce emissions.

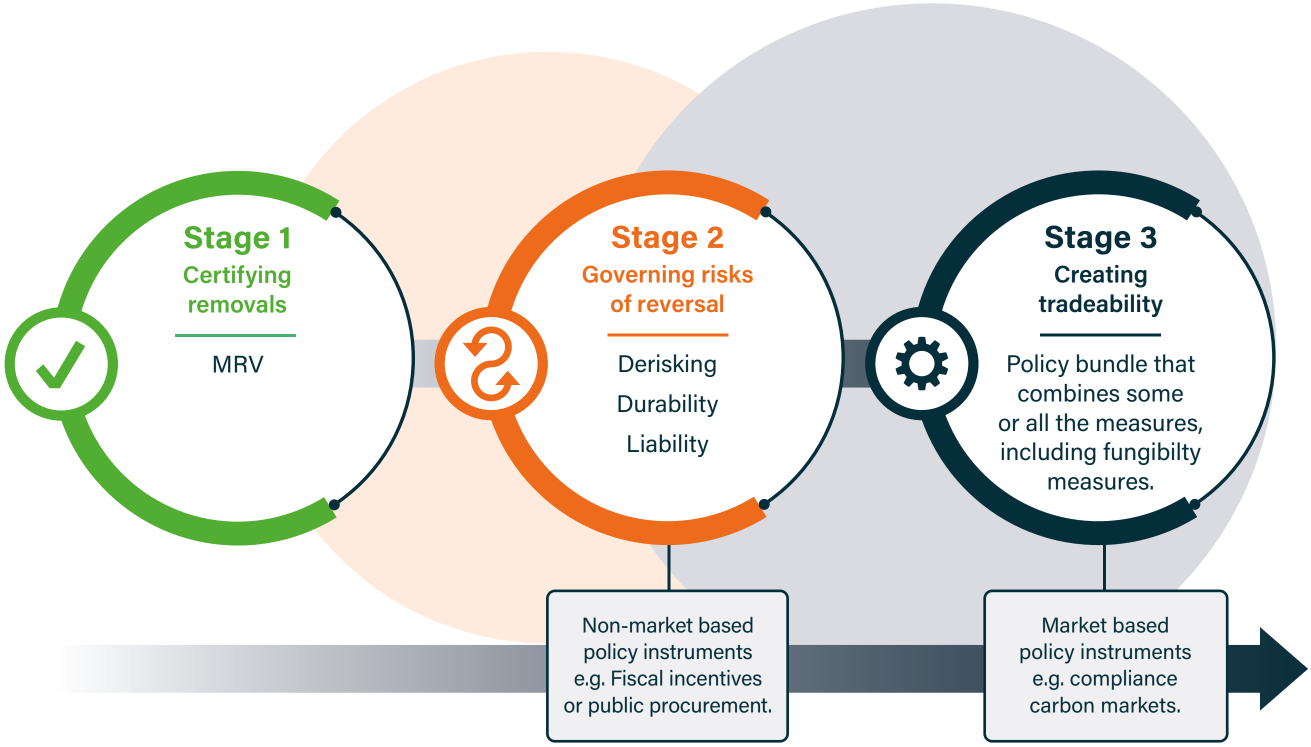

Figure ES2: Three-stage conceptual sequencing for CDR policy.

Risk of misplaced fungibility

At the heart of this is whether the codification of CO_2, as a tangible commodity provides CDR with absolute fungibility with established emissions reductions measures. Implicit in this assumption is that a tonne of CO_2 sequestered by biotic sinks can be made equivalent to either a tonne of CO_2 captured by solutions with durable permanent geological storage such as Bio-Energy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS), or emissions reductions. But this fails to recognise carbon that is stored for only a short duration that expires before global temperature stabilisation is achieved will not contribute to temperature stabilisation outcomes.

Such an approach must recognise the distinctive contexts in which these very different solutions operate, and the risks embedded within them, especially as it can be difficult to scientifically or economically define the equivalence between one CDR unit generated through a given technique and one positive emissions unit abated.

Another important dimension is economic equivalence. These approaches offer a quantitative methodology to create fungibility. Whilst this provides a framework to make difficult policy choices tractable, it is important to recognise potential shortcomings including the tension between technocratic responses available to policymakers and the broader social, economic and political issues that will influence outcomes. The recent vote by the EU Committee on Agriculture and Rural Development to classify biochar as a permanent carbon store alongside BECCS and DACCS illustrates the attempts of powerful actors to shape the permanence frameworks that will govern them.Certification schemes in particular, such as the carbon removal certification framework (CRC-F) in the EU, are therefore – although quite technical – an arena for political struggles over the future of specific CDR methods.

"Determining what is fungible depends on nuanced concepts in climate science, climate economics, and real-world market practices."

The politics of carbon removal accounting are illustrated by the critical normative assumptions that underpin economic approaches to valuing temporary and permanent CDR. Small differences in assessing storage times, the social cost of carbon, future discount rates or future removal costs can imply dramatic environmental and economic implications for society. If removed CO_2 is re-emitted and removals are not renewed, such an outcome is inconsistent with the Paris Agreement and could breach domestic carbon budgets. Determining what is fungible depends on nuanced concepts in climate science, climate economics, and real-world market practices. Fungibility should therefore not be skated over or simply cast as technocratic and value-free.

A conceptual framework for thinking about fungibility

Fungibility is easier to operationalise if technological functions are viewed as having standardized effects. Subject to the appropriate application of measures outlined in Figure ES1, it may be possible to standardize groups of CDR methods, based on their level of permanence. A helpful way to conceptualize this is by thinking of fungibility in terms of intra and inter-fungibility. Intra-fungibility (i.e vertical fungibility) refers to fungibility across CDR methods with broadly the same level of permanence. Inter-fungibility (i.e. horizontal fungibility) refers to fungibility between CDR methods with different levels of permanence. **The classifications of storage duration are based on those set out by the IPCC**. Classifications are not intended to be fixed in perpetuity. As new evidence emerges, CDR methods may be reclassified to have either longer or shorter carbon storage durations.

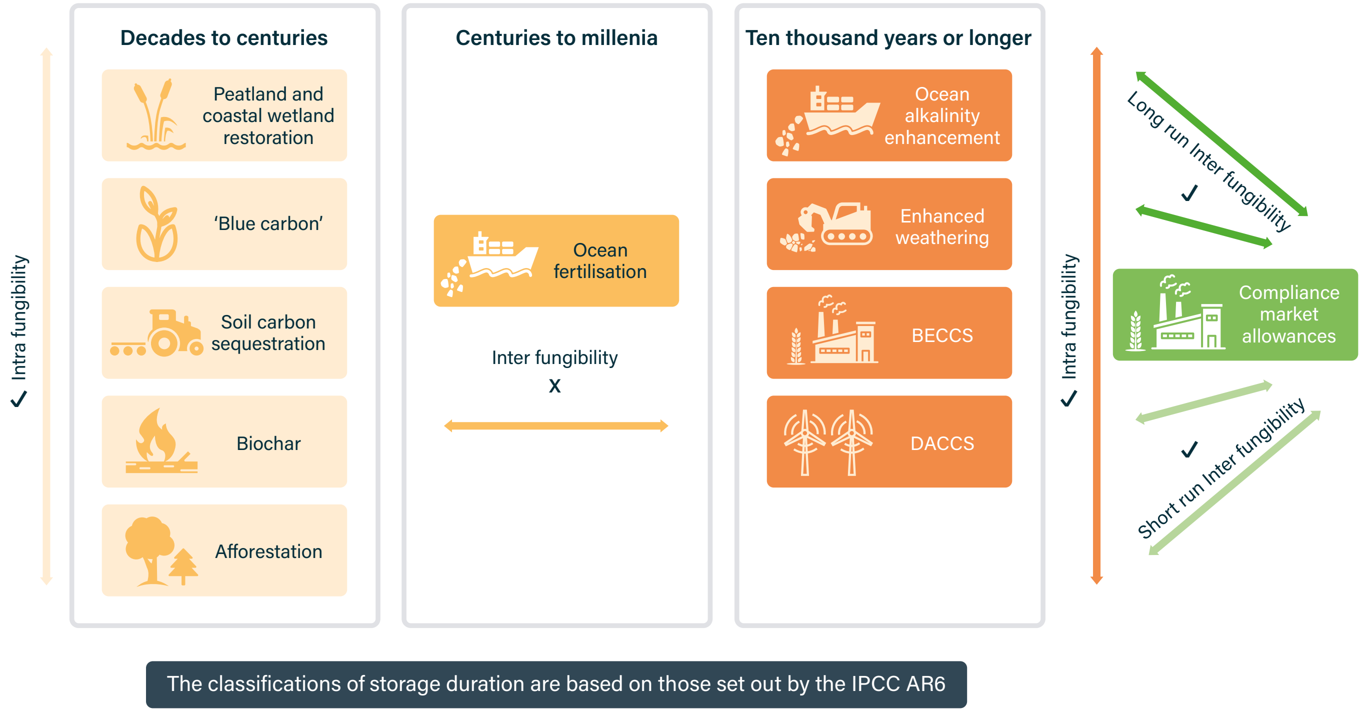

Figure ES3: Intra and inter-fungibility. Classifications based on IPCC definitions.

Intra-fungibility for methods with decades to centuries opens up the possibility of a separate standalone carbon market for these non-permanent CDR or the integration in to an ETS that only covers land use and agricultural emissions. Alternatively, bespoke policy frameworks for individual methods such as the UK Woodland Carbon Code for afforestation or Label bas Carbon in France for a suite of CDR methods could provide a different route to market. Both approaches would channel finance to these projects but critically it would undo equivalences and avoid the challenges of inter-fungibility. Creating a viable business case for non-permanent CDR is critical as we need a diverse portfolio of CDR – especially those that are most scalable in the short term – to support the diversity of risk by each CDR type.

By only examining the time value of CDR, we may undervalue important co-benefits derived from non-permanent CDR, including their ability to protect, conserve, restore and sustainably use terrestrial, freshwater, coastal and marine ecosystems.

Although inter-fungibility is theoretically possible through the application of equivalence ratios, standardization between near permanent and non permanent methods could mask differences and risks. This includes lack of real fungibility between emissions reductions and non-permanent removals, the potential for CDR to act as an emission reduction deterrent and the risks associated with the genuine permanence and environmental integrity of the CDR technique, namely additionality and durability/permanence.

The framework set out above suggests that if CDR that stores carbon for decades to centuries is not fungible with CDR which stores carbon for centuries to millennia or ten thousand years or more, it is therefore not fungible with compliance market allowances. Hence, not all CDR can be traded in one harmonised carbon market as poor substitutability between CDR and emissions reductions could be obscured under a policy framework that promotes carbon markets. This has implications for policymakers seeking to include afforestation or other non-permanent CDR within compliance markets. Only CDR that stores carbon for ten thousand years or more might be considered fungible with compliance market allowances.

Conclusion

Measures that govern CDR permanence are important to scale up and deliver the removal capacity required in most net-zero modelling scenarios. Yet, to date there does not appear to be a clear understanding of the extent to which different permanence measures are required for different methods. This report sets out a framework for assessing how different levels of permanence can be governed, with the aim to analyse options for CDR policy sequencing for carbon removal. The results presented in this paper are subject to the uncertainty inherent to the data and assumptions used to estimate storage duration. It is possible that not all mechanisms have been captured.

"Measures that govern CDR permanence are important to scale up and deliver the removal capacity required in most net-zero modelling scenarios."

Introduction

Why is Carbon Dioxide Removal needed?

Carbon dioxide removal (CDR) from the atmosphere is an inevitable component of operationalizing net-zero targets into practical climate policy. Indeed, integrated assessment model pathways that limit warming to 1.5 degrees Celsius include – in addition to deep reductions of gross greenhouse gas emissions – a massive scale up of CDR methods (IPCC, 2022). The IPCC envisions three complimentary and strategic roles for CDR; further reducing net CO_2 or GHG emission levels in the near-term; to counterbalance residual emissions from hard-to-transition sectors (emissions typically related to aviation, long-distance transportation, structural materials, heavy industry, and agriculture); and to achieve and sustain net-negative CO_2 or GHG emissions in the long-term (Babiker et al., 2022). With the proliferation of net-zero targets in many jurisdictions the importance of CDR as part of mitigation strategies has increased substantially, both nationally and internationally.

Policy context

Explicit CDR policy frameworks and implementation strategies are nascent and vary between jurisdictions. The United States for example, has announced plans for a government led procurement scheme in order to stimulate demand as well as generous subsidies for Direct Air Capture (DAC) through 45Q and the Inflation Reduction Act. The integration of CDR into existing compliance carbon markets is an alternative approach. One that has unsurprisingly gathered greater traction in the EU and the UK since large scale compliance carbon markets are already in operation (i.e., the EU and UK ETS). In the EU at least it is still an open question if CDR will be included in the ETS. In contrast, the UK Government has signalled stronger intent.

In June 2023, the UK Government gave a clear indiciation that they view compliance carbon markets as an appropriate long term policy instrument to stimulate demand for CDR in the UK. The recent consultation response on the development of the UK ETS (UK ETS Authority, 2023) states that the "Authority believes that the UK ETS is an appropriate long-term market for CDR" and that the "authority intends to include engineered greenhouse gas removals (GGRs) in the UK ETS, subject to further consultation". This is welcome as existing policy mechanisms tend to support only established afforestation and soil carbon sequestration methods and although geological storage is covered in some policies, the incentives they provide are inadequate (Hickey et al., 2023).

"Carbon markets offer a helpful way to involve emitters from hard-to-abate sectors. However, the definition of 'hard to abate' is not well defined conceptually or quantitatively."

The authority's more cautious language on the inclusion of less permanent CDR in the UK ETS (UK ETS Authority, 2023) recognises that there may need to be some differentiation based on permanence of storage (Honegger et al., 2021). The development of certifications schemes – such as the EU Carbon Removal Certification Framework (CRC-F) – to define different types of carbon removals and monitor, report and verify the authenticity of these removals is a prerequisite for integration within ETS's (Schenuit et al., 2023), and deployment under alternative policy instruments.

Carbon markets offer a helpful way to involve emitters from hard-to-abate sectors. However, the definition of 'hard to abate' is not well defined conceptually or quantitatively (Buck et al., 2023). Consequently, the level of unabated emissions that are considered 'acceptable' and thus 'residual' is contingent on values, norms and interests (Lund et al., 2023). The inclusion of CDR in the compliance market carries the risk, depending on the carbon price and the cost of removal, that emissions that are not normally considered hard-to-abate will be offset with removal credits. At the same time, however, integrating CDR into compliance markets engages hard-to-abate sectors in creating a demand for CDR. The relatively minor role these sectors play in the current CDR market is striking. As major emitters and the main users of CDR under net-zero, it seems reasonable to expect a prominent contribution to market development from those sectors.

A fundamental challenge is that emissions trading schemes are presently designed to handle only positive emission caps (Bednar et al., 2021) and are not compatible with the target of net-zero. New allowances in the UK and EU ETS are expected to end around 2040. With a tighter cap, prices are expected to rise. Excessive CO_2 price spikes and volatility has the potential to undermine the political acceptance and support for emissions trading as a central climate policy instrument (Rickels et al., 2022). Pahle et al., (2023) describe this as the 'ETS endgame' where supply approaches zero and the market will undergo changes or even cease to function. In order to enhance liquidity and maintain their role as a cornerstone of UK and EU climate policy, ETS's must successfully evolve to include CDR and transition from a positive to a net-zero compatible emissions trading system (ICAP, 2021). In part, CDR inclusion is being driven by these pressures, rather than whether the policy is a first best solution to financing the net negative economy.

> ***"A fundamental challenge is that emissions trading schemes are presently designed to handle only positive emission caps." (Bednar et al., 2021)***

It is conceivable that the integration of CDR into emissions trading schemes could weaken the ambition to reduce gross emissions in some sectors. To mitigate this, a credible dynamic price cap and market stabilisation could be supported by the 'conditional integration' of CDR. Conditionally based upon factors such as levels of permanence, future abatement potential and carbon removal cost of specific methods as well as overarching carbon market developments has the potential to stipulate learning-by-doing for carbon removal methods in the short-term without undermining learning-by-doing in the emissions abatement sector (Rickels et al., 2022).

> ***"It is conceivable that the integration of CDR into emissions trading schemes could weaken the ambition to reduce gross emissions in some sectors."***

CDR methods have different characteristics which limit fungibility

Despite the common feature of removing carbon dioxide, CDR methods can be very different. Implementation strategies need to reflect that different methods such as Direct Air Carbon Capture and Storage (DACCS), Bio-Energy with Carbon Capture and Storage (BECCS), afforestation, ocean fertilisation and biochar have very different characteristics in terms of their cost, technological maturity, storage duration, risk of reversal and additionality (i.e., that the carbon removed by a project or activity is over and above what would have happened in its absence). Important differences in removal processes and storage duration are outlined in Figure 1 and these IPCC timescales of storage underpin the storage duration assumptions used in this report.

How long different CDR methods can store carbon matters fundamentally for the economics of CDR, the specific technology's role for climate policy and the optimal governance and regulatory framework (Edenhofer et al., 2023). Whilst non-permanent CDR is not equivalent to near permanently stored CDR or emissions abatement it is not of zero value (Prado and Macdowell, 2023). It 'buys time' for society to develop and deploy alternative mitigation actions (Brandão and Levasseur, 2011). Temporary CO_2 removal can also have some climate repair value when deployed as a short-term mechanism to limit climate damage by delaying, reducing, and flattening CO_2 levels, and temperature (Lygnfelt et al., 2019), but this is contingent on peak warming having occurred by the time of reversal of the temporary CO_2 sink (Chiquer et al., 2022). However, benefits of temporary removals only accrue if they are used in additional to fossil fuel reduction, not as offsets (Mathews et al., 2022).

"How long different CDR methods can store carbon matters fundamentally for the economics of CDR, the specific technology's role for climate policy and the optimal governance and regulatory framework."

On the other hand, widespread deployment of non-permanent CDR increases the burden (and management liability of non-permanent sinks) on future generations to ramp up mitigation efforts yet further and incur the costs of permanently removing carbon that is released from non-permanent CDR. Additionally, the implementation of reliable monitoring, reporting and verification (MRV) and accounting systems for non-permanent storage entails a higher administrative burden – and always the risk of loopholes and inaccuracies, especially increasingly fragile LULUCF sinks in the context of ongoing climate change. Kalkuhl et al. (2022) compare the task of continuous maintenance of that CO_2 sink, or subsequent replacement by permanent CO_2 removal with Sisyphus' task of rolling the big rock up a hill only to let it slip and watch it roll down to the bottom again. Failure to recognise this risk is thus an unacceptable shift of the mitigation burden to future generations with large implications for intergenerational equity (Brandao et al., 2013)

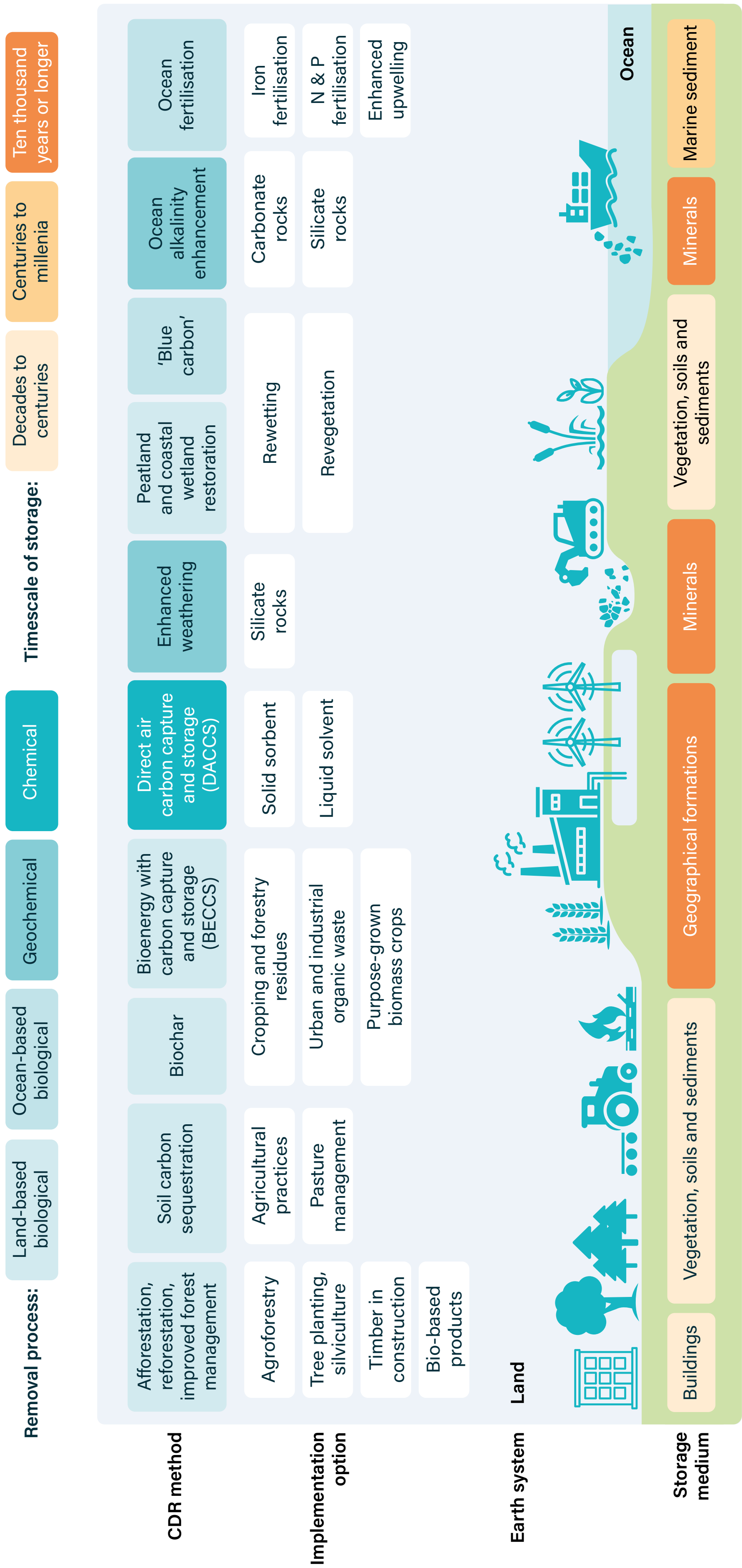

Figure 1: CDR ecosystem. Source: IPCC AR6 WGIII.

A further risk is that if all types of CDR become integrated in markets, 'artificially cheap' certificates from non-permanent methods could dominate the market for CDR. These low prices would be a risk for more permanent and additional CDR methods like BECCS and DACCS since capital flows would likely be directed to lower cost and already available solutions. Resulting low prices would provide insufficient demand pull for more expensive, emerging technologies like BECCS and DACCS, undermining the business case to deploy them at scale (Schenuit et al., 2023).

For CDR units to operate efficiently within compliance carbon markets CDR units must be tradeable with fossil CO_2 emissions (Prado and Macdowell, 2023). In other words, heterogeneous CDR units must be considered to have equivalent value and therefore be comparable and interchangeable for the purposes of settling compliance obligations in a given carbon market.

"For CDR units to operate efficiently within compliance carbon markets CDR units must be tradeable with fossil CO_2 emissions."

One element inhibiting the development of these markets is the absence of an accessible and agreed upon framework for evaluating the quantitative relationship between 1 tonne CO_2 stored 'permanently' and 1 tonne CO_2 stored over a shorter time period. Put another way, how and to what extent can the heterogenous characteristics of different CDR methods (durability bounds, risk of reversal, MRV precision etc) be assessed in order to ascribe fungibility against both credits from different CDR methods and against GHG emission units. How these issues are addressed in practice can have a significant impact on the environmental and climate integrity of strategies to facilitate the integration of CDRs into the compliance markets.

Aim of this report

The use of CDR and their potential inclusion in carbon markets raises a number of critically important questions. Is this politically feasible and desirable? If so, what types of CDR could be considered tradeable with emissions reductions in compliance markets? How, and through which criteria, can tradeability be created? Can the risks associated with different levels of permanence be appropriately governed? How might regulations be designed to balance reversal risk and public buy in whilst supporting innovation and market scaling?

In response to this emerging policy context, a number of proposals have been put forward, each addressing distinct challenges posed by different levels of permanence. Whilst this is often framed as a way of creating fungibility, these proposals in fact deal with a broader set of risks. Yet a synthesis of individual measures, and an assessment of their possible combination in practice and policy sequencing strategies has yet to be done. This policy report seeks to map the status quo and propose a typology of policy measures and bundles that can be used to help address the challenging questions on permanence, and tradeability in CDR policymaking. Whilst this typology of measures has its genesis in the voluntary carbon market it is also intended to help those designing similar measures for future compliance markets too or alternative policy instruments.

Governing permanence

In the following, we first map different groups of measures related to efforts to govern for the permanence of different removals. In a second step, we propose a policy sequencing structure for developing credible rules in CDR policy. Based on this, we then identify illustrative policy bundles for CDR policies.

A combination of web-based keyword searches, reviews of policy documents and interviews with stakeholders were used to identify measures. Figure 2 illustrates the various measures identified and structures them into two distinct but interrelated tiers.

Tier 1: MRV as a foundational measure

The first tier is about 'foundational measures' for permanence accounting as a prerequisite for creating fungibility.

A practical starting point for any permanence accounting is Monitoring, Reporting and Verification (MRV) schemes which assess the veracity of a carbon removal claim. MRV schemes can provide assurance that removals are additional and not harmful to local environments or communities. MRV is not considered an optional measure, but MRV should apply to all removals that are integrated in accounting and market structures. The scale of the challenge should not be underestimated, both scientifically and politically. Indeed, the history of certified emissions reductions (CER) under the Kyoto Protocol, for example, including the differentiation between "long-term" and "temporary" CERs shows that many of these questions are not new. Therefore, policymakers should consider developing and regulating minimum standards for MRV as well as actionable governance structures to apply them in emerging CDR policy designs (Mercer and Burke, 2023).

Tier 2: Building blocks of Governing permanence

The second tier consists of more specific groups of measures, each addressing distinct governance challenges that arise from different levels of permanence.

That said, the measures should not be viewed as mutually exclusive but as complimentary and interconnected. A multiplicity of combinations are possible. Each measure has equal weighting although their application will vary depending on the market structure and the CDR method. It is important to note that some of these measures are already addressed in voluntary carbon markets, especially those related to the governing the risk of reversal. The relationship to emissions reductions, however, will have to receive more attention in the ongoing transition from voluntary to compliance markets.

De-risking measures include financial carbon insurance and market discount rates/ratings agencies. The former provides financial compensation in the event of a project failure (i.e. reversal) and can be procured by buyers or sellers as a way of underwriting risk. In the event of a non-delivery, a compensation payment is made. Carbon insurers are now also offering to procure CDR to replace any lost units, in lieu of cash payments. The development of carbon assets to underpin insurance seems a sensible market development. Like debt rating, carbon rating agencies issue ratings to assess the quality of carbon removal projects to help buyers better understand the risks associated with a carbon removal project's delivery risk or credit quality. This can be further developed under the concept of a risk adjusted return whereby ratings agencies can develop their own market discount rates to calculate a percentage discount to the type of carbon removal being delivered. Carbon removal ratings agencies remain nascent, and their role, methodologies and financial incentives should be scrutinised as best practice becomes clearer in the process of establishing credible CDR accounting.

Durability measures refer to the risk that certain types of carbon removal may be more prone to reversal where carbon is re-released into the atmosphere due to extreme weather events, disease, site/facility maintenance or poor land use governance. The main measure is the use of buffer pools whereby carbon removal projects contribute credits to the buffer pool based on either a suite of project-specific risk factors that determine individual project contribution rates or a flat contribution rate that applies to all projects. Buffer pool credits are then retired as needed to cover carbon losses from events such as wildfire or drought (Badgley et al., 2022). Buffer pools are typically held by registries and are typically designed in three ways. First, all projects within the registry program are combined in a single pool. Second, they can be divided by project type and third, they can be individually linked to specific projects. Whether the state or private actors are in control of the buffer pool and associated governance architecture will have to be decided in future CDR policy.

Fungibility measures attempt to quantitatively value CDR with different levels of permanence, from which equivalence ratios can be produced. Equivalence ratios describe how many tonne of CO_2 need to be temporarily stored to account for an additional tonne of CO_2 emitted to the atmosphere today. A higher equivalence ratio means that more temporary storage is needed to make a given claim in order to fulfil compliance obligations; a lower ratio requires less (Carbon Plan, 2022). For example, the output from an equivalence ratio might suggest that 3 non-permanent CDR credits are equal to 1 permanent CDR credit. Equivalence ratios can be calculated using physical approaches or economic approaches.

Physical equivalence requires a 1:1 relationship between physical climate outcomes, like cumulative radiative forcing. When comparing carbon storage to emissions, a physical equivalence claim requires that the storage durability matches the atmospheric lifetime of CO_2. This approach omits normative assumptions such as time horizons and discount rates.

Economic approaches attempt to balance the economic benefits of temporarily reducing warming against the economic costs of longer-term climate damages. A number of approaches have emerged. Economic appraisals usually derive the value from carbon prices and discount rates (Parisa et al., 2022) or are measured in terms of economic damages avoided, using the social cost of carbon as a proxy, but modifying this to take into account duration, and risks of non-additionality and failure (Groom and Venmans, 2023). Rather than explicitly creating equivalence ratios, a climate repair value (CRV) seeks to quantify the damage function of varying permanence and incorporate this in a conventional levelized cost of removal analysis, extended to account for monitoring, reporting, and verification (MRV) of a given store (Prado and Macdowell, 2023). Whilst similar, tonne year accounting uses an even narrower set of parameters to directly value carbon storage based on its duration, but this does not include time horizons beyond 100 years or factors such as additionality, levelized cost, MRV, long-term climate effects, or risk of failure.

Liability measures refer to a set of mechanisms that stipulate the storage duration period and legally obligate companies to continually remove carbon in the event of a reversal or at the end of a project lifespan. This makes sure that permanent emissions are being offset by impermanent but recurring removals. This typically refers to projects that store carbon for decades to centuries since managing contracts over these time periods is more manageable. Two types of liability measures are proposed. The first is to make CDR companies a compliance entity within compliance markets. By doing this firms supplying non-permanent CDR could surrender allowances according to the released carbon at the end of their non-permanent removal projects.

The second option is to mandate perpetual removal through different types of continuous obligations that sit outside of a compliance market. This includes bundling, where different CDR methods are bundled into pools that can generate standardised units (Macinante and Ghaleigh, 2022). Ex-ante purchasing is another option whereby CDR is bought via advance market commitments and then issued at the point of re-release for a non-permanent project. Unlike buffer pools which set aside a quantity of removals at the start of a project (i.e ex-post risk management), ex-ante purchasing allows projects hedge future risk by purchasing forward capacity. This therefore deals with the risk in the future. The last option is to contemporaneously purchase units from a new carbon removal project at the point of re-release, assuming that such CDR capacity is available.

The transition from Voluntary Carbon Market to compliance markets may make some measures less salient. However, how the measures are combined will depend on the type of CDR method, the approach of integrating CDR into climate policy and the envisioned role of government in this, as well as the compliance market design. The application of each measure and the combination of measures for different CDR methods is discussed in chapter 4.

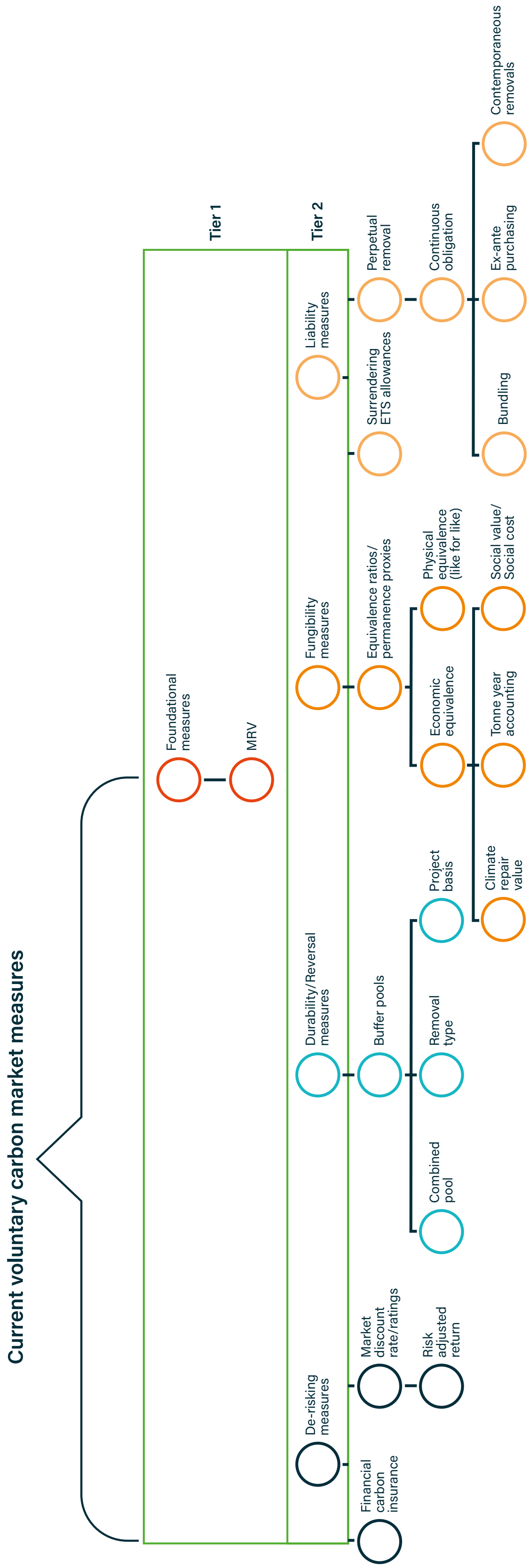

Figure 2: Governing permanence: Typology of measures.

Policy sequencing: a three-stage approach

As a second stage after the mapping of existing measures and for the purposes of practical CDR policymaking, we suggest a three-stage conceptual policy sequencing for the five groups of measures (MRV, de-risking, durability, fungibility, liability) identified in the mapping above. Policy sequencing is a key strategy of climate policymaking and proved to be successful in overcoming political challenges in other areas of decarbonization strategies (e.g. Meckling et al., 2017). In the emerging literature on CDR policy, this approach has also been identified as an important strategy (e.g. Wähling et al., 2023; Zetterberg et al., 2021). In order to create policy instruments to govern the permanence of removals, we propose a sequence of the following three steps, each stage representing an increased integration of CDR into climate policy, up to measures that collectively create tradeability of CDR units with ETS allowances, i.e. a de-facto fungibility required to facilitate the integration into compliance markets (see Figure 3).

The first stage, as already indicated by the two tiers in the measure mapping, is to attain **credible certification** of removal activities via the foundational measure of a MRV scheme (see also previous chapter). Such a scheme is the prerequisite for any CDR policy that aims at integrating removal activities into climate policymaking. In addition to transparent accounting protocols, such endeavours must take into account the different permanence characteristics, as well as system boundaries of various CDR methods, including indirect emissions across the whole process chain as well as other sustainability criteria.

In the second stage, a sequencing strategy to govern permanence should contain measures to **govern the risks of reversal.** This stage is already necessary for the initial steps of CDR policy, e.g. result-based subsidy schemes for CDR deployment. To govern permanence transparently and effectively, a range of measures are available (see de-risking, durability, and liability measures in Figure 2). The importance and operationalization of sets of measures for managing reversal risks will differ depending on the selected CDR method. Less permanent methods require a broader set of de-risking, durability, and liability measures. More permanent removal methods, however, should also be covered by liability measures in the event of leakage or reversal. The application of permanence measures is good practice for a broad range of non-market-based policy instruments and will play an important role in upcoming CDR policy initiatives. For example, if governments are attempting to scale CDR via result-based subsidies or public procurement (e.g. carbon contract for difference, or feed-in-tariffs), liability arrangements and buffer pools help to govern the risk of reversal.

In a third step, when CDR policy aims for the integration into market-based policy instruments such as compliance carbon markets, CDR policy will have to establish tradeability of CDR certificates and ETS allowances. This is not to imply that all CDR policymaking must adopt the suggested sequencing's third phase. CDR can be integrated into climate policy architectures without creating tradeability. However, it is a prerequisite for trading emissions and removals within the same compliance market. Thus, the third stage of implementing CDR policy requires enacting regulations regarding the equivalence of emissions reductions and removals. This can be achieved by designing a holistic policy package that combines some or all the measures in the typology, rather than just using 'fungibility measures' in isolation (see Figure 3).

In this context, it is crucial to exercise responsible decision-making, not just for technical matters relating to economic and physical equivalence but also for the political implications associated with these decisions. Careful consideration must be given to the issue of moral hazard, especially due to the fact that incorporation into the carbon market has the potential to impede efforts to reduce emissions. Merely implementing cost-benefit equivalence (which underpins many economic equivalence approaches) measures is inadequate to address this challenge. It is expected that such integration into compliance markets would not work without a prior phase of subsidies, as at current levels of cost for high quality removals and allowances, it would be a weak driver for scaling up CDR (Burke and Gambhir, 2022).

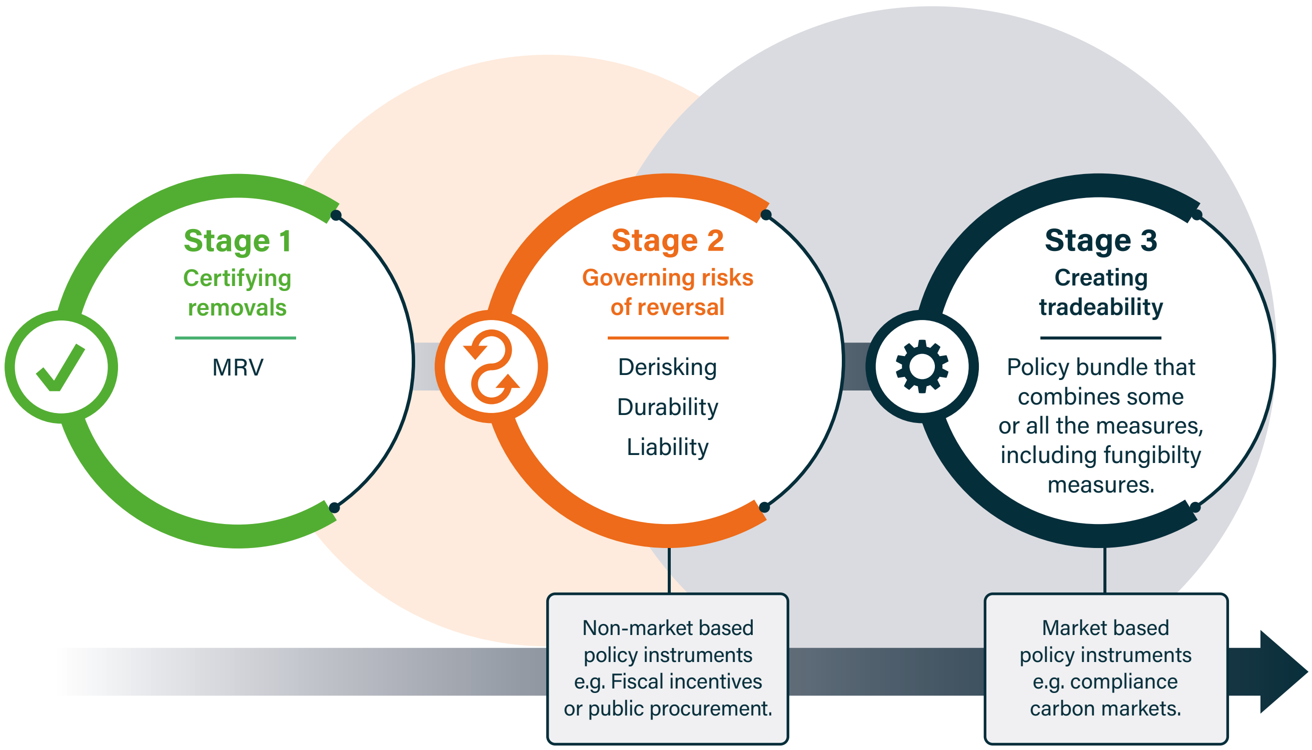

Figure 3: Three-stage conceptual sequencing for CDR policy.

Illustrative policy bundles

The following chapter seeks to illustrate how individual measures outlined in the typology and the sequencing could be applied to CDR with different levels of permanence. The purpose of the policy bundles is to illustrate how different risks might be managed, by whom and under what policy frameworks. This is a 'mapping exercise' that tries to organize and provide guidance for policy makers that face the challenge of operationalizing the integration of a portfolio of different CDR methods into climate policy. The bundles are illustrative and not intended to be prescriptive. Indeed, they must be adaptable and respond flexibly as technologies mature and novel approaches emerge. Foundational measures (MRV and liability measures) are the only exception which need to apply to all CDR regardless of differing permanence and policy/market design. The bundles cannot solve all practical questions that will come up in facilitating the integration in practice; but they help by structuring complex debates on CDR policy designs and can inform the decision about whether and how different types of removals should be considered fungible with emissions reductions.

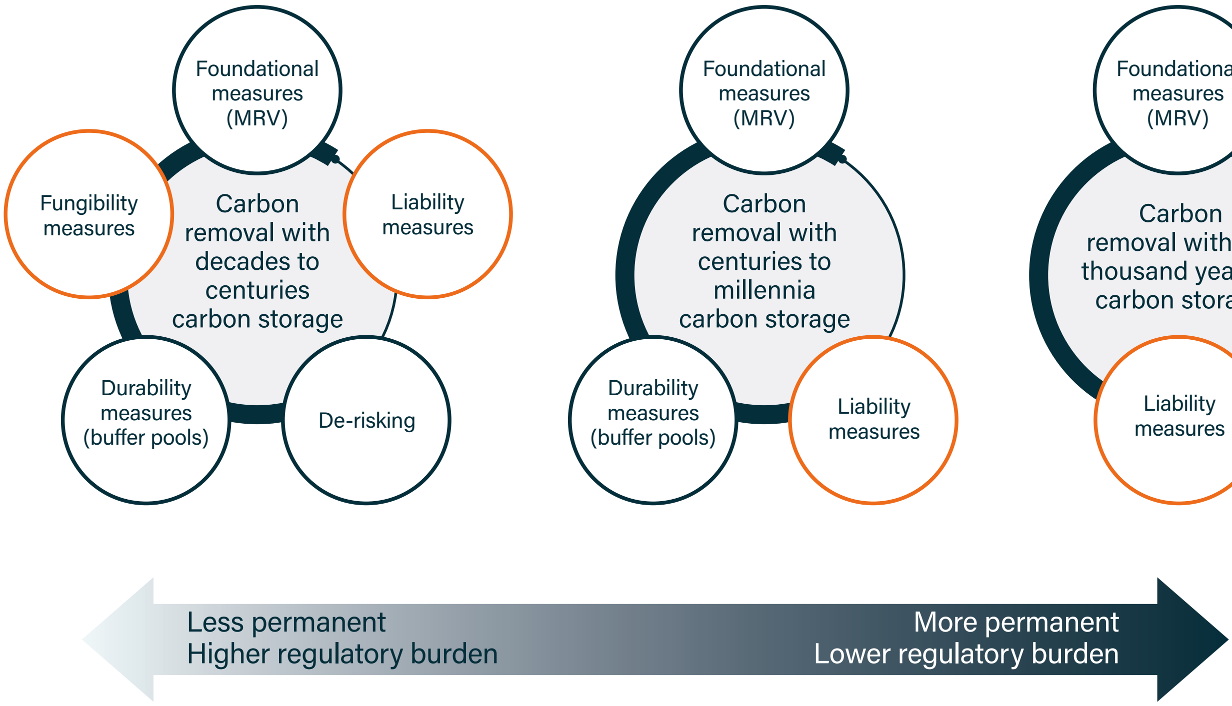

Figure 4: Illustrative policy bundles. Small blue circles are those that are currently employed in the VCM. Small orange circles are additional measures that might be used in lieu or as a complement in a compliance carbon market.

CDR with ten thousand years or longer of carbon storage

Different CDR approaches require different policy support based on permanence factors. Carbon removal with ten thousand years or longer of carbon storage requires (e.g. BECCS and DACCS) less accompanying policies since it has a high permanence level. Low reversal risk and high additionality implies that durability measures and fungibility measures are less likely to be needed. Intuitively this feels appropriate since policymakers need to be cognizant of not overburdening comparatively expensive, but more durable CDR, especially as these need to significantly scale.

Foundational measures (MRV) are still required in addition to policy measures that account for storage liability. This could either be in the form of perpetual removal or via the surrendering of ETS allowances. The latter becomes an option since high levels of permanence make it possible to be fungible with abatement and therefore suited to carbon market inclusion. The surrendering of permanent CDR allowances would likely necessitate the need to liquidate regular allowances in order to effectively lower the cap in line with expectations, or other forms of managing the cap, e.g. through a new institution such as a carbon central bank (Rickels et al., 2022). Although de-risking measures would not necessarily be mandated in a compliance market and their role would be outside the direct purview of policymakers, there may still be a role for ratings agencies or insurance providers to play. But their exact role depends on the several uncertain policy design and governance parameters, including the role of government as the arbiter of CDR quality, and where the competency for implementing methodologies, certification and re-certification sits.

> ***"Carbon removal with ten thousand years or longer of carbon storage requires (e.g. BECCS and DACCS) less accompanying policies since it has a high permanence level."***

CDR with centuries to millenia carbon storage

Carbon removal with centuries to millennia carbon storage (e.g ocean macronutrient fertilization) has a higher reversal risk and so liability and durability measures should be utilized. Foundational measures are particularly important here as open-loop CDR such as ocean fertilization has potentially big advantages in terms of thermodynamic efficiency (enhancing pre-existing natural CDR processes can be more efficient, cost-effective and scalable) and long-run scalability over closed-loop CDR (i.e. where CO_2 is drawn down from ambient air through approaches which capture, contain and store CO_2 with a much higher degree of human intervention across all steps of the CDR process). Without strong MRV and credible removal certificates, market confidence in these processes can be undermined, halting capital flows, and stymying innovation and policy development.

CDR with decades to centuries of carbon storage

As non-permanent CDR presents more risks, naturally this requires a more substantive set of policies. This is evident when looking at CDR with decades to centuries carbon storage. CDR methods in this category, such as afforestation, biochar and soil carbon sequestration are currently subject to foundational measures (MRV), durability measures (buffer pools) and de-risking measures in the VCM. Since these measures have been predominantly operationalized in the VCM, they represent private rather than public sector initiatives. Whilst buffer pools do operate in some compliance markets – such as the Californian ETS – they are measures to manage the temporary nature of land-based offsets rather than for CDR specifically. As such, buffer pools for CDR, provided through registries are currently a private sector measure. In integrating these methods into compliance markets, policy makers are confronted with the tension between sufficient and responsible governance and over-regulation that stifles the market. A potentially dysfunctional regulatory architecture resulting from this tension could also impact other CDR methods and slow the spread of all forms of removal. As with CDR methods that store carbon for centuries to millenia, credible MRV schemes are essential. Imprecise and opaque schemes do not only provide risks for greenwashing, they also pose a risk for the upscaling of high quality removals.

Application of permanence measures in public policy

The application of fungibility measures remains largely theoretical. There are however, some real-world applications of other permanence measures in public policy, of which liability measures and durability measures (buffer pools) are the most prevalent (Arcusa and Hagood, 2023). In general, the combination of measures tend to be far less stringent than those outlined in Figure 3 and are limited to a number of examples. In addition to the California ETS, the UK Woodland Carbon Code (WCC) only makes use of publicly owned buffer pools in conjunction with MRV and liability measures. The liability measures are termed 'Contractual Obligations' which commits landowners to a permanent land use change to woodland, and to maintain the woodland as a woodland carbon sink. However, it is unclear what kind of continuous obligation this enforces (bundling, ex-ante or contemporaneous).

Similarly, under the Carbon Farming Initiative, forestry, revegetation and soil carbon projects in the Australian Government Emission Reduction Fund are subject to durability measures and liability measures to manage permanence risks. Non-permanent projects also have the option of choosing a shorter permanence period, for example, by operating for 25 years rather than 100. But credits issued for those projects will be discounted by 20 per cent. Buffer pool requirements still apply for discounted projects, although this regulatory requirement is low at just 5% of credits (Australian Government, 2014).

In contrast, the New Zealand ETS employs a different kind of liability measure – the surrendering of ETS allowances – whereby participants are liable to surrender to the government an equivalent number of ETS units if the credited forestry removals are reversed. The unit repayment liability in these cases reduces emissions elsewhere in the system by liquidating other allowances to maintain the overall cap. This is intended to ensure landowners compensate for any reversals of credited forestry removals in a way that maintains the original benefits to the climate. This contrasts with project crediting mechanisms which typically maintain a buffer of uncredited forest reserves to compensate for future reversals (Carver, 2022).

Regardless of whether policymakers seek to include non-permanent CDR methods within a compliance carbon market, it seems prudent that policy design is guided by the precautionary principle and as a minimum, MRV and buffer pools continue to be deployed, refined and strengthened. In particular, buffer pools need to be well capitalized, particularly if credits in the buffer pool are cross-fungible. Moreover, buffer pools need the ability to dynamically respond to unexpected changes to the carbon stock since up-front allocation to a buffer pool places an expectation on future stakeholders to not allow releases from past credits in excess of the pool, yet provides them with no incentive to do so (Balmford et al., 2023). Combining buffer pools with ongoing MRV after credit issuance and liability measures and/or insurance can ensure that any credits that experience a reversal can be replaced.

If in the future policymakers do seek to try and integrate non-permanent CDR methods within compliance markets, a further set of measures is likely to be needed. This includes de-risking measures, fungibility measures and updated liability measures that enforce continuous obligations. Because of the substantial uncertainty over permanence, policymakers should go beyond the bare minimum, for practical and normative reasons.

Long-term risks of non-permanent removals

Neither enhanced liability measures or fungibility measures is without risk. Perpetual removal for non-permanent CDR in particular comes with its own set of challenges. Non-permanent removals imply a liability for actors in the value chain. This liability is subject to substantial risk since the marginal costs of abatement tend to increase over time with deployment, particularly for land management options (Fuss et al., 2018). Increasing removal costs make it more costly to finance recurring debt and thus to finance perpetual removal in the future. What appears to be cheap removal in the land sector in the short-term actually imply large future costs when the non-permanence is accounted for.

A good illustration of this in the UK Woodland Carbon Code is the price differential between Woodland Carbon Units (WCU) – which represents a tonne of CO_2 taken from the atmosphere today – and a Pending Issuance Unit (PIU) – which is a promise to deliver a WCU in the future. The cost of a WCU is roughly double that of a PIU. Regulating contemporaneous removal instead of ex-ante purchases may seem preferable since it pushes the financial obligation out in to the future, but it could be a far more financially burdensome measure at the end of a project lifespan or in the event a reversal occurs.

The continued operation of the firm in which the liability is attached to is therefore critical. If the firm goes out of business, for example in case of bankruptcy, diligence and the ability to continuously remove carbon would drop to zero. This could result in an undesirable transfer of risks from private to public bodies if there is a default and the government is the de facto backstop. For countries with short term carbon budgets, like the United Kingdom, this could imply legal risks. A significant reversal event has the potential to breach carbon budgets unless there is a mechanism to compensate for this in the requisite timescales. Strong regulatory guardrails will be needed to prevent this. Financial assurance could play a role here whereby firms needing assurance are made to purchase it in the form of insurance or other surety obligations. Historic precedents exist within natural resource extraction industries. In the event mining companies declare bankruptcy to avoid legal obligations to remediate mining sites, insurance can ensure obligations can be acted upon beyond the lifetime of a company.

Assuming a company remains solvent, there also needs to be a liquid market in which ex-ante or contemporaneous purchases can be made. Perissa et al., (2022) further ague that existing methodologies for managing risk – namely the long-term liability contracts – impose substantial additional burdens on project developers, whereas an economic approach based on a formula is much simpler as economic equivalence offers a means of replacing perpetual removal contracts with simpler, easy to execute short-term contracts.

Bringing together the approaches to govern the *risk of reversal* and the *relationship to emissions reduction* can turn out to be challenging in practice. It could be argued that fungibility measures obviate the need for durability measures, since they already account for impermanence. Although they appear to be different sides of the same coin, they deal with distinct issues. Buffer pools deal with the physical risk of reversal and tend to be more dynamic in nature, while equivalence ratios put an economic value on temporary storage and are more static. As the objectives are different, so are the assumptions that underpin each calculation and therefore each may arrive at very different outcomes when it comes to determining how many additional permits should be surrendered or set aside for every tonne removed. It is therefore conceivable that both policies could work in tandem, especially as once discount rates are formalized, it may reduce the incentive to continually monitor.

Moreover, it is critical that fungibility measures do not obfuscate important differences in CDR credit quality. Markets that sell CDR credits need more transparency, not less. A spectrum of costs needs to be visible, reflecting the diversity of carbon-removal approaches, rather than a single price for removing one tonne of CO_2 (Boyd et al., 2023). Evidence from the voluntary carbon market suggests a willingness from buyers to purchase removal credits with high impact scores (Boston Consulting Group, 2023). In other words, buyers were unwilling to consider the lowest quality credits. To allow this choice to be made in compliance markets, it is imperative that price discovery is not lost under a policy framework that standardises all CDR units, which could disadvantage more costly but high-quality CDR options.

Taxonomy of policy preferences

The right combination of measures will also reflect choices between different risk preferences or political priorities in climate policymaking. Even though CDR policies appear to be quite technical, especially in the context of establishing fungibility, their designs are a political choice as much as an economic or scientific one. Below we illustrate a taxonomy of risk and policy preferences as an alternative but complimentary framework for exploring, analyzing, and discussing preferences. The taxonomy presented in Figure 4 is not exhaustive. Rather, it is intended to serve as a helpful starting point and other risk and policy preferences could be added depending on the priorities and interests of policymakers.

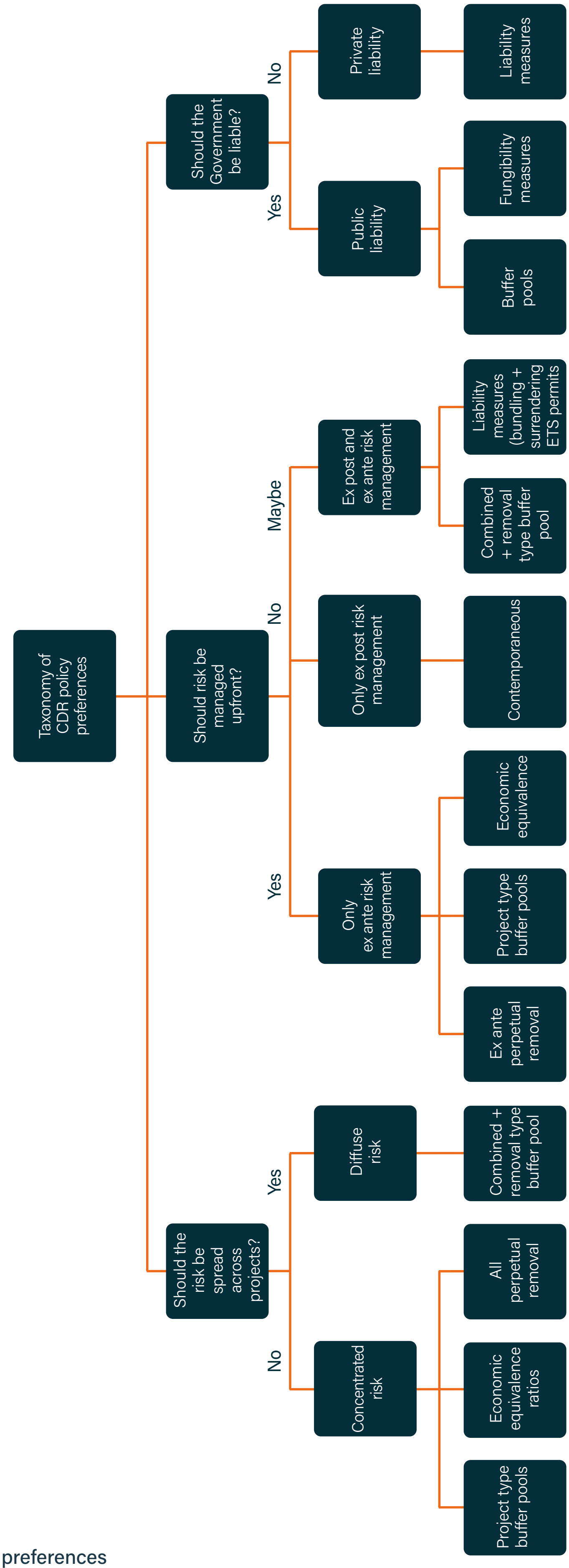

Figure 5: Taxonomy of policy preferences

Three different basic policy preferences are presented. Starting on the left-hand side, policymakers could choose whether their preference was to allocate the risk of impermanence to individual projects or whether that risk should be hedged across a portfolio of projects. If there is a preference for the former, three options are available. This includes project specific buffer pools, economic equivalence ratios and all forms of perpetual removal (see Figure 2). In contrast, the risk could be spread across a number of CDR projects in two ways – either through combined buffer pools or removal type buffer pools. Spreading the risk across projects may enhance the depth and resilience of the buffer pool but may increase administratively complexity for policy makers as it requires other projects and project types to be of equivalent quality. For example, if credits in the buffer pool are cross-fungible, a risk-specific analysis is needed across multiple projects and buffer pools to identify whether a particular risk factor is undercapitalized or overcapitalized in the current buffer pool.

The second policy principle is whether to manage the risk of reversal in advance of a reversal event (ex-ante), at the point reversal (ex-post) or whether to retain flexibility to do both. If reversal risk should be managed in advance there are three policy options. The first is ex-ante perpetual removal, the second is project type buffer pools and the third is by using economic equivalence measures. Baking in risk at the start is in some ways safer because preventative measures are taken in advance, which may be beneficial depending on the future cost of removals as outlined previously. However, this relies on the Government getting this estimate correct – particularly when designing fungibility measures and buffer pools – with consequences for getting this wrong. For example, underestimating the equivalence ratio would reduce the ability of policymakers to flexibly respond in the short run compared to buffer pools.

If policymakers would rather deal with risk as and when it occurs, there is only one option – contemporaneous removals. From a climate repair standpoint, the contemporaneous and permanent removal of CO_2 is consistently observed to be the best way to fully compensate for emissions that are too costly to directly abate (Prado and Macdowell, 2023). Moreover, by dealing with reversals when they happen, it removes the need for government to estimate the risk in advance – but it relies on having robust and deliverable mechanisms to deal with the reversal risk when it happens. Not least the solvency of a firm to deal with large and perhaps even infinite recurring debt in the case of non-permanent removals and potential leakage risks associated with CCS-based methods and the development of a liquid market for removals to compensate for this risk in the future. Managing ex-post and ex-ante risk simultaneously could be achieved using combined and removal type buffer pools or liability measures including bundling and surrendering EU ETS permits.

Lastly, the question of where the liability for reversal sits is a particularly pertinent question. Governments may have good reason to place the liability on either sellers or developers rather than on the Government balance sheet. If the liability should be managed publicly, government operated buffer pools or fungibility measures would achieve this. If the preference was to place the liability on the private sector, liability measures are the only option. In practice it may not be reasonable to think of liability between the private CDR transactors (via sellers, buyers and developers) and the country (i.e public sector) in which activities take place as completely binary, since under the Paris Agreement countries with NDCs face de facto liability for carbon reversals from storage sites that they host. In both cases, questions remain over institutional capacity and feasibility, as very few human institutions have persisted for more than a few hundred years.

The challenge of both frameworks is finding a balance between policies that manage risks without stifling innovation. This becomes less of an issue if non-permanent removal is deemed to be non-fungible with permanent CDR and conventional abatement.

"The challenge of both frameworks is finding a balance between policies that manage risks without stifling innovation."

Risk of misplaced fungibility

At the heart of this is whether the codification of CO_2 as a tangible commodity provides CDR with absolute fungibility with established emissions reductions measures. Implicit in this assumption is that a tonne of CO_2 sequestered by biotic sinks can be made equivalent to either a tonne of CO_2 captured by solutions with durable permanent geological storage such as BECCS or DACCS, or emissions reductions. But this fails to recognise carbon that is stored for only a short duration that expires before global temperature stabilisation is achieved will not contribute to temperature stabilisation outcomes (Cullenward, 2023).

Such an approach must recognise the distinctive contexts in which these very different solutions operate, and the risks embedded within them, especially as it can be difficult to scientifically or economically define the equivalence between one CDR unit generated through a given technique and one positive emissions unit abated. Markusson et al., (2021) see misplaced fungibility as a critical problem for CDR. Most significantly, they suggest that treating emissions reductions and removals as entirely fungible allows for undesirable substitution, resulting in "mitigation deterrence." There is also a need to examine different forms of equivalence such as carbon, geographical, and temporal equivalence, which all have implications for temperature overshoot and climate justice (Carton et al., 2021). Geographical equivalence is perhaps less of a concern if all CDR used for meeting compliance obligations has to originate from within the same jurisdiction as it would negate any differences across locations in terms of their biophysical and socio-political characteristics.

Another important dimension is economic equivalence. These approaches offer a quantitative methodology to create fungibility. Whilst this provides a framework to make difficult policy choices tractable, it is important to recognise potential shortcomings including the tension between technocratic responses available to policymakers and the broader social, economic and political issues that will influence outcomes. The recent vote by the EU Committee on Agriculture and Rural Development to classify biochar as a permanent carbon store alongside BECCS and DACCS illustrates the attempts of powerful actors to shape the permanence frameworks that will govern them. Certification schemes in particular, such as the CRC-F in the EU, are therefore – although quite technical – an arena for political struggles over the future of specific CDR methods. Actors with stakes in CDR development and deployment are aware of the key role of MRV and accounting schemes, which is why their design will become increasingly contested.

The politics of carbon removal accounting are illustrated by the critical normative assumptions that underpin economic approaches to valuing temporary and permanent CDR. Small differences in assessing storage times, the social cost of carbon, future discount rates or future removal costs can imply dramatic environmental and economic implications for society. Instead of taking the Paris Agreement goal of temperature stabilisation as a given, economic equivalence methods 'optimise' theoretical cost-benefit calculations and can end up justifying outcomes with higher warming levels (Carbon Market Watch, 2023). Brander and Broekhoff (2023) further describe these approaches as problematic as temporarily storing carbon out of the atmosphere does not mitigate long-term temperature change, which is predominantly driven by cumulative CO_2 emissions.

If removed CO_2 is re-emitted and removals are not renewed, such an outcome is inconsistent with the Paris Agreement and could breach domestic carbon budgets. Determining what is fungible depends on nuanced concepts in climate science, climate economics, and real-world market practices. Fungibility should therefore not be skated over or simply cast as technocratic and value-free.

The ability to put an economic value on a major decision with seeming rigour is understandably appealing to policymakers as a means of justifying their choices (Coyle et al., 2023). However, undoing these equivalences would better account for the potential for impermanent implementation, failure, or non-additionality (Calel et al., 2021) arising from poor land use governance, extreme weather events, disease or the absence of strong institutions to enforce monitoring, reporting and verification (MRV). Earlier iterations of the voluntary carbon market (VCM) or the Kyoto Protocol's Clean Development Mechanism (CDM) where these issues persisted has led to doubts about whether fungibility is possible or desirable.

"Determining what is fungible depends on nuanced concepts in climate science, climate economics, and real-world market practices."

It may never be possible to have certainty that a tonne of CO_2 sequestered by a land-based sink is equivalent to either a tonne of CO_2 captured by BECCS or DACCS, or an abated tonne of CO_2. Expectations for policy that attempts to reconcile these challenges may need to be dampened and policy frames adapted accordingly. But rather than undoing equivalence between emissions reductions and all CDR, a distinction could be made between different CDR methods, for example, near permanent and non-permanent CDR. This is explored further in the following chapter.

A conceptual framework for thinking about fungibility

As outlined in chapter 1, creating tradeability (de-facto fungibility) is a prerequisite for the integration of CDR into compliance markets. Given the substantial differences of CDR methods in terms of permanence, we propose a conceptual framework to distinguish types of removal activities that can be considered fungible. Fungibility is easier to operationalise if technological functions are viewed≈as having standardized effects (Lohmann, 2005).

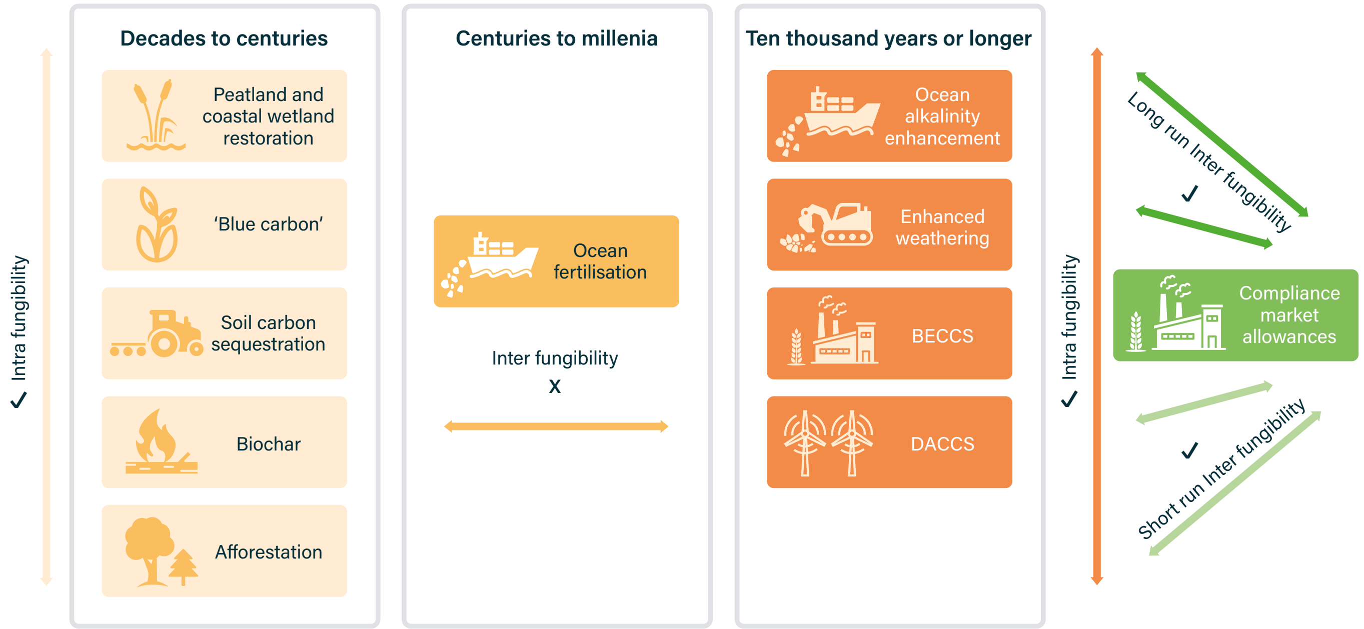

Figure 6: Intra and inter-fungibility. Classifications based on IPCC definitions.

Subject to the appropriate application of measures outlined in Figures 1 and 2, it may be possible to standardize groups of CDR methods, based on their level of permanence. A helpful way to conceptualize this is by thinking of fungibility in terms of intra and inter-fungibility. Intra-fungibility (i.e vertical fungibility) refers to fungibility across CDR methods with broadly the same level of permanence. Inter-fungibility (i.e., horizontal fungibility) refers to fungibility between CDR methods with different levels of permanence and those that are addressed by the different illustrative policy bundles. Like above, the classifications of storage duration are based on those set out by the IPCC (see also Figure 1). Classifications are not intended to be fixed in perpetuity. As new evidence emerges, CDR methods may be reclassified to have either longer or shorter carbon storage durations. It is vital to note that while certain CDR methods may be considered intra-fungible, they may have varying co-benefits or negative outcomes – factors that, alongside the carbon stored, ought to be taken into account in responsible CDR policy.

"As new evidence emerges, CDR methods may be reclassified to have either longer or shorter carbon storage durations."

Intra-fungibility for methods with decades to centuries opens up the possibility of a separate standalone carbon market for these non-permanent CDR or the integration in to an ETS that only covers land use and agricultural emissions. This has potential as the low permanence can then be used to balance out non-CO_2 emissions in the agricultural sector rather than fossil CO_2 emissions from other sectors. Temporary storage is far more likely to be economically equivalent with non-CO_2 emissions such as methane due to their shorter atmospheric lifetimes. This would be akin to a physical equivalence approach.

Alternatively, bespoke policy frameworks for individual methods such as the UK Woodland Carbon Code for afforestation or Label bas Carbon in France for a suite of CDR methods could provide a different route to market. Both approaches would channel finance to these projects but critically it would undo equivalences and avoid the challenges of inter-fungibility. Creating a viable business case for non-permanent CDR is critical as we need a diverse portfolio of CDR – especially those that are most scalable in the short term – to support the diversity of risk by each CDR type (Nemet et al., 2018). By only examining the time value of CDR, we may undervalue important co-benefits derived from non-permanent CDR, including their ability to protect, conserve, restore and sustainably use terrestrial, freshwater, coastal and marine ecosystems.

Although inter-fungibility is theoretically possible through the application of equivalence ratios, standardization between near permanent and non-permanent methods could mask differences and risks. This includes lack of real fungibility between emissions reductions and non-permanent removals, the potential for CDR to act as an emission reduction deterrent and the risks associated with the genuine permanence and environmental integrity of the CDR technique, namely additionality and durability/permanence. In particular there is a lack of fungibility between 'biotic' carbon (i.e. that which is part of the active carbon cycle, such as from land use) and 'fossil' carbon (i.e. that which is locked away in fossil fuels). Non-permanent biotic solutions are far more prone to reversal than CDR methods that store carbon in geological formations. Inclusion of non-permanent CDR in carbon markets therefore raises important considerations and costs for regulation and temporal governance in relation to monitoring, reporting and verification (MRV) (Cox et al., 2018). When the ongoing MRV costs and the probability of reversal are accounted for this suggests that permanent removals will be economically preferable in the long-term even though non-permanent removals may appear to be more cost-effective in the short term (Prado and Macdowell, 2023).

Considering additional factors

When deciding whether it is appropriate to include non-permanent CDR in carbon markets, additional factors also need to be considered. For example, the distinction needs to be made between CDR methods that will be likely to be additional – often more expensive permanent CDRs that will not depress the market price and CDRs that may never be additional – often cheap with the potential to depress the market prices (Burke and Gambhir, 2022). This points to a second set of challenges that might arise without adjustments to emissions caps, tighter restrictions on eligible CDR, or new governance structures to manage supply and demand imbalances. Even with these additional safeguards, the reaction of market participants may still be divorced from market fundamentals. Indeed, just the perception that policy changes reduce stringency can lead to carbon price depression.

Moreover, current low observed prices within global compliance carbon markets – where the global average is roughly $3 (IMF, 2021) – may provide insufficient demand pull to drive currently more-costly CDR methods to deployment at commercial scales. Daggash and Macdowell (2019) suggest that even a social cost of carbon that peaks at £349/tCO_2 in 2075 from £6/tCO_2 in 2015 is insufficient to kickstart deployment of BECCs and DACCS throughout this time period.

It has also been argued that using compliance carbon markets to drive demand for land based CDR may increase competing demands for land. This may result in undesirable land use change whereby competing priorities for farmland conflicts with food sovereignty and livelihoods (Dooley et al., 2022).

Takeaways from the framework

The conceptual framework set out above suggests that if CDR that stores carbon for decades to centuries is not fungible with CDR which stores carbon for centuries to millennia or ten thousand years or more, it is therefore not fungible with carbon market allowances. Hence, not all CDR can be traded in one harmonised carbon market as poor substitutability between CDR and emissions reductions could be obscured under a policy framework that promotes carbon markets. This has implications for policymakers seeking to include afforestation or other non-permanent CDR within compliance markets. Indeed, due to these challenges, the Climate Change Committee (CCC) recommended not including non-permanent solutions in the UK ETS as they cannot be relied on to have sufficient permanence (CCC, 2022).

Only CDR that stores carbon for ten thousand years or more might be considered fungible with compliance market allowances. But given the varying levels of technical maturity even within this classification and the vastly different MRV readiness between methods such as BECCS and DACCS compared to enhanced weathering and ocean alkalinity enhancement (OAE), not everything in this group is currently fungible with compliance market allowances because of disparities in foundational (MRV) measures. Figure 3 illustrates that BECCS and DACCS have the potential for short run fungibility, meaning that the timeline for carbon market integration is a near to medium term option, because MRV methodologies are clearer and the technologies represent near permanent removals. In contrast, enhanced weathering and OAE have the potential for long run fungibility due to their high levels of permanence, but this is only a long term option due to the complexity and immaturity of MRV protocols.

Moving forward, a number of design options are conceivable. Ohlendorf (2023) and Theur et al., (2021) have identified a number of proposals for designing compliance market for CDR. These include fully disconnected markets, fully integrated markets, partial integration (only certain CDR can be used) and connected markets with quantitative and qualitative restrictions (all CDR can be used subject to limits).

Our conceptualisation of intra- and inter-fungibility outlined above suggests that integration of permanent CDRs can be a reasonable way forward, which – if based on credible MRV systems, liability measures and fungibility/durability measures – can help achieve three different policy objectives: making compliance markets compatible with net-zero targets, enabling market uptake of removals in the medium term, and avoiding moral hazard in integrating CDRs into climate policy architectures. The practical implementation of such integration of permanent removals requires future research. A key objective of this future work should be to facilitate mutual learning between different compliance markets, in particular between those that have already taken the first steps towards CDR integration and those that are preparing to do so.

Conclusion and recommendations

Measures that govern CDR permanence are important to scale up and deliver the removal capacity required in most net-zero modelling scenarios. Yet, to date there does not appear to be a clear understanding of the extent to which different permanence measures are required for different methods. This report sets out a framework for assessing how different levels of permanence can be governed, with the aim to analyse options for policy sequencing and the construction of robust permanence bundles for carbon removal. The results presented in this paper are subject to the uncertainty inherent to the data and assumptions used to estimate storage duration. It is possible that not all mechanisms have been captured.

Our analysis suggests that no single mechanism will be sufficient across the full range of CDR methods or policies. As non-permanent CDR presents more risks, naturally this requires a more substantive set of permanence measures. Similarly, integration of CDR into compliance markets also requires the application of a number of permanence measures in order to establish tradeability of CDR certificates and ETS allowances.

Overall, determining what is fungible in emissions and removals accounting or tradeable in compliance markets depends on nuanced concepts in climate science, climate economics, and real-world market practices. Fungibility should therefore not be skated over or simply cast as technocratic and value-free. Small difference in critical normative assumptions that underpin economic approaches to valuing temporary storage – such as assessing storage times, the social cost of carbon and future discount rates – can imply dramatic environmental and economic implications for society. These approaches can end up justifying outcomes with higher warming levels.

There are several implications for policy. First, non-permanent CDR that is released before peak warming needs a continuous obligation to remove CO_2 and is not equivalent to permanent CDR or emissions reductions. Second, what appears to be cheap removal in the land use sector imply when the cost of governing impermanence are accounted for. This suggests that permanent removals will be economically preferable in the long-term. Third, not all CDR can be traded in one harmonised carbon market as poor substitutability between CDR, conventional mitigation or emissions reductions could be obscured under a policy framework that promotes carbon market integration.

Based on this we make the following recommendations:

1. Foundational measures (MRV) should come first in the policy sequencing and apply to all CDR regardless of differing permanence and policy/market design. As a minimum, these measures need to be refined and strengthened. Policymakers should also consider developing and regulating minimum standards for MRV.
2. Policymakers seeking to include afforestation or other non-permanent CDR in a compliance carbon market should prohibit their use and set minimum storage durability and sustainability requirements.
3. Policymakers should promote a spectrum of visible costs within policy frameworks, reflecting the diversity of carbon-removal approaches.
4. Bespoke policy frameworks for non-permanent CDR are needed to provide a different route to market. This could include subsidies for land-based removals or the integration into a separate ETS that only covers land use and agricultural emissions and removals. Non-permanent CDR can be used to balance out non-CO_2 emissions in the agricultural sector with shorter atmospheric lifetimes.

References

1. Arcusa, S. and Hagood, E . (2023). Definitions and mechanisms for managing durability and reversals in standards and procurers of carbon dioxide removal," OSF Preprints 6bth5, Center for Open Science.
2. Australian Government. (2014). Emissions reduction fund white paper. Available: www.dcceew.gov.au/sites/default/files/documents/erf-white-paper.pdf
3. Babiker, M., G. Berndes, K. Blok, B. Cohen, A. Cowie, O. Geden, V. Ginzburg, A. Leip, P. Smith, M. Sugiyama, F. Yamba. (2022). Cross-sectoral perspectives. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (P.R. Shukla,J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)). Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.005
4. Badgley, G., Freeman, J., Hamman, J. J., Haya, B., Trugman, A. T., Anderegg, W. R. and Cullenward, D. (2021). Systematic over-crediting in californias forest carbon offsets program. Global Change Biology, doi:https://doi.org/10.1111/gcb.15943
5. Balmford, A., Keshav, S., Venmans, F. et al. Realizing the social value of impermanent carbon credits. Nat. Clim. Change. https://doi.org/10.1038/s41558-023-01815-0
6. Bednar, J., Obersteiner, M., Baklanov, A. et al. (2021). Operationalizing the net-negative carbon economy. Nature 596, 377–383. https://doi.org/10.1038/s41586-021-03723-9
7. Boston Consulting Group. (2023). In the voluntary market buyers will pay for quality. Available: www.bcg.com/publications/2023/why-vcm-buyers-will-pay-for-quality
8. Boyd, P., Bach, L., Holden, R and Turney, C. (2023). Carbon offsets aren't helping the plant-four ways to fix them. Nature 620, 947-949. https://doi.org/10.1038/d41586-023-02649-8
9. Brander, M., Broekhoff, D. (2023). Discounting emissions from temporarily stored carbon creates false claims on contribution to cumulative emissions and temperature alignment. SSRN Journal. https://doi.org/10.2139/ssrn.4353340
10. Brandão, M. and Levasseur, A. (2011). Assessing temporary carbon storage in life cycle assessment and carbon footprinting, Report JRC. doi: 10.2788/22040
11. Brandao, M., Levasseur, A., Kirschbaum, M. U. F., Weidema, B. P., Cowie, A. L., Jørgensen, S. V., Hauschild, M. Z., Pennington, D. W., & Chomkhamsri, K. (2013). Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. International Journal of Life Cycle Assessment, 18(1), 230-240. https://doi.org/10.1007/s11367-012-0451-6
12. Buck, H. J., Carton, W., Lund, J. F., & Markusson, N. (2023). Why residual emissions matter right now. Nature Climate Change, 1–8. https://doi.org/10.1038/s41558-022-01592-2
13. Burke, J., and Gambhir, A. (2022). Policy incentives for Greenhouse Gas Removal Methods: The risks of premature inclusion in carbon markets and the need for a multi-pronged policy framework | Elsevier Enhanced Reader. Energy and Climate Change. https://doi.org/10.1016/j.egycc.2022.100074
14. Calel, R., Colmer, J., Dechezleprêtre, A and Glachant, Matthieu. (2021). Do Carbon Offsets Offset Carbon? CESifo Working Paper No. 9368, Available at SSRN: https://ssrn.com/abstract=3950103
15. Carbon Market Watch (2023). Mortgaging the atmosphere: why temporary storage is eisky and cannot replace emissions reductions. Available: https://carbonmarketwatch.org/publications/mortgaging-the-atmosphere-why-temporary-carbon-storage-is-risky-and-cannot-replace-emission-reductions/
16. Carbon Plan (2022). Unpacking ton-year accounting. Available: https://carbonplan.org/research/ton-year-explainer

17. Carver, T., Dawson, P and Kerr, S, (2017). Including Forestry in an Emissions Trading Scheme: Lessons from New Zealand. Available at SSRN: https://ssrn.com/abstract=3015082

18. CCC (2022). Letter: development of the UK Emissions Trading Scheme. Available: www.theccc.org.uk/publication/letter-development-of-the-uk-emissions-trading-scheme-uk-ets/

19. Chiquer, S., Patrizio, P., Bui, M., Sunny, N., and Mac Dowell, N. (2022). A comparative analysis of the efficiency, timing, and permanence of CO_2 removal pathways. Energy Environ. Sci. 15, 4389–4403. https://doi.org/10.1039/D2EE01021F

20. Carton, W., Lund, J. F., & Dooley, K. (2021). Undoing equivalence: Rethinking carbon accounting for just carbon removal. Frontiers in Climate. https://doi.org/10.3389/fclim.2021.664130

21. Coyle, D., Fabian, M.,, Beinhocker, E., Besley, T and Stevens, M. (2023). Is it time to reboot welfare economics? Overview. Fiscal Studies, 44 (2). 109 – 121. https://doi.org/10.1111/1475-5890.12334

22. Cox EM, Pidgeon N, Spence E and Thomas G. (2018). Blurred Lines: The Ethics and Policy of Greenhouse Gas. Removal at Scale. Front. Environ. Sci., 6:38. doi: 10.3389/fenvs.2018.00038

23. H.A. Daggash, N. Mac. (2019). Higher Carbon Prices on Emissions Alone Will Not Deliver the Paris Agreement Joule, 3, pp. 2120-2133, 10.1016/j.joule.2019.08.008

24. Cullenward, D. (2023). The climate value of temporary storage. Available: https://carbonmarketwatch.org/wp-content/uploads/2023/09/FINAL-CMW-version-of-temporary-storage-paper.pdf

25. Edenhofer, O., Franks, M., Kalkuhl, M and Runge-Metzger, A. (2023). On the Governance of Carbon Dioxide Removal – a Public Economics Perspective. CESifo Working Paper No. 10370, Available at SSRN: https://ssrn.com/abstract=4422845

26. Fuss S, Lamb W, Callaghan M, Hilaire J, Creutzig F et al. (2018). Negative emissions – Part 2: Costs, potentials and side effects. Environmental Research Letters, 13. 10.1088/1748-9326/aabf9f

27. Dooley K., Keith H., Larson A., Catacora-Vargas G., Carton W., Christiansen K.L., Enokenwa Baa O., Frechette A., Hugh S., Ivetic N., Lim L.C., Lund J.F., Luqman M., Mackey B., Monterroso I., Ojha H., Perfecto I., Riamit K., Robiou du Pont Y., Young V. (2022). The Land Gap Report 2022. Available at: https://www.landgap.org/

28. Groom, B., Venmans, F. (2023). The social value of offsets. Nature 619, 768–773 https://doi.org/10.1038/s41586-023-06153-x

29. Hickey, C., Fankhauser, S., Smith, S and Allen, M. (2023). A review of commercialisation mechanisms for carbon dioxide removal. Frontiers in Climate. 4. 1101525. 10.3389/fclim.2022.1101525.

30. Honegger, M., Poralla, M., Michaelowa, Axel; Ahonen, Hanna-Mari. (2021). Who Is paying for carbon dioxide removal? Designing policy instruments for mobilizing negative emissions technologies. Frontiers in Climate, 3:672996. DOI: https://doi.org/10.3389/fclim.2021.672996

31. ICAP (2021). Emissions Trading Systems and Net-Zero: Trading Removals. Available: https://icapcarbonaction.com/en/publications/emissions-trading-systems-and-net-zero-trading-removals

32. IMF (2021). Five things to know about carbon pricing. Available: www.imf.org/en/Publications/fandd/issues/2021/09/five-things-to-know-about-carbon-pricing

33. IPCC (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf

34. Kalkuhl, M., Franks, M., Gruner, F., and Lessmann, K and Edenhofer, O. (2022). Pigou's Advice and Sisyphus' Warning: Carbon Pricing with Non-Permanent Carbon-Dioxide Removal. CESifo Working Paper No. 10169, Available at SSRN: https://ssrn.com/abstract=4315996

35. La Hoz Theuer, S., Doda, B., Kellner, K. and Acworth, W. (2021). Emission Trading Systems and Net-Zero: Trading Removals. Berlin: ICAP. Available: https://icapcarbonaction.com/en/publications/emissions-trading-systems-and-net-zero-trading-removals

36. Lohmann, L. (2005). Marketing and making carbon dumps: Commodification, calculation and counterfactuals in climate change mitigation. Sci. Cult., 14 (2005), pp. 203-235, 10.1080/09505430500216783

37. Lund, F, Markusson, N., Carton, W & Buck, H. (2023). Net-Zero and the unexplored politics of residual emissions, Energy Research and Social Science, 98, 103035. https://doi.org/10.1016/j.erss.2023.103035

38. Lyngfelt, A., Johansson, Daniel and Lindeberg, E. (2019). Negative CO_2 Emissions – An Analysis of the Retention Times Required with Respect to Possible Carbon Leakage. Available at SSRN: https://ssrn.com/abstract=3366366 or http://dx.doi.org/10.2139/ssrn.3366366

39. Macinante, J and Ghaleigh, NS. (2022). Regulating Removals: Bundling to Achieve Fungibility in GGR 'Removal Units.' Edinburgh School of Law Research Paper No. 2022/05, Available at SSRN: https://ssrn.com/abstract=4064970

40. McLaren, D, Tyfield, D, Willis, R, Szerszynski, B & Markusson, N. (2019). 'Beyond 'Net-Zero': A case for separate targets for emissions reduction and negative emissions,' Frontiers in Climate, 1, 4. https://doi.org/10.3389/fclim.2019.00004

41. Markusson, N., McLaren, D and Tyfield, D. (2919). Towards a cultural political economy of mitigation deterrence by negative emissions technologies (NETs) Glob. Sustain. 10.1017/sus.2018.10

42. Meckling, J., Sterner, T. & Wagner, (2017). G. Policy sequencing toward decarbonization. Nat Energy 2, 918–922. https://doi.org/10.1038/s41560-017-0025-8

43. Mercer, L. and Burke, J. (2023). Strengthening MRV standards for greenhouse gas removals to improve climate change governance. London: Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy, London School of Economics and Political Science. Available: https://www.lse.ac.uk/granthaminstitute/publication/strengthening-mrv-standards-for-greenhouse-gas-removals/

44. Nemet, G. F., Callaghan, M. W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., et al. (2018). Negative emissions—Part 3: innovation and upscaling. Environ. Res. Lett. 13, 063003. doi: 10.1088/1748-9326/aabff4

45. Meyer-Ohlendorf, N. (2023): Making Carbon Removals a Real Climate Solution. How to integrate carbon removals into EU Climate Policies. Berlin: Ecologic Institute.

46. Pahle, M., Günther, C., Osorio, S and Quemin, S. (2023). The Emerging Endgame: The EU ETS on the Road Towards Climate Neutrality. Available at SSRN: https://ssrn.com/abstract=4373443

47. Parisa Z., Marland, E., Sohngen, B., Marland, M and Jenkins, J. (2022). The time value of carbon storage. Forest Policy and Economics, Volume 144,2022,102840, ISSN 1389-9341, https://doi.org/10.1016/j.forpol.2022.102840

48. Prado, A and Mac Dowell, N. (2023). The cost of permanent carbon dioxide removal,Joule, Volume 7, Issue 4, Pages 700-712, ISSN 2542-4351, https://doi.org/10.1016/j.joule.2023.03.006

49. Rickels, W., Rothenstein, R., Schenuit, F and Fridahl, M. (2022). Procure, Bank, Release: Carbon Removal Certificate Reserves to Manage Carbon Prices on the Path to Net-Zero, Energy Research & Social Science, Volume 94, 102858, https://doi.org/10.1016/j.erss.2022.102858

50. Schenuit, F., Gidden, M.J., Boettcher, M. et al. (2023). Secure robust carbon dioxide removal policy through credible certification. Commun Earth Environ 4, 349. https://doi.org/10.1038/s43247-023-01014-x

51. S and P Global (2023) UK carbon prices dive to multi-year lows, EU ETS disconnect widens. Available: www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/053123-uk-carbon-prices-dive-to-multi-year-lows-eu-ets-disconnect-widens

52. UK ETS Authority (2023). Developing the UK Emissions Trading Scheme: Main Response. Available: www.gov.uk/government/consultations/developing-the-uk-emissions-trading-scheme-uk-ets

53. Wähling, L-S., Fridahl, M., Heimann, T., Merk, C. (2023). "The Sequence Matters: Expert Opinions on Policy Mechanisms for Bioenergy with Carbon Capture and Storage." Energy Research & Social Science 103, 103215. https://doi.org/10.1016/j.erss.2023.103215

54. Zetterberg L, Johnsson F and Möllersten K (2021) Incentivizing BECCS—A Swedish Case Study. Front. Clim. 3:685227. doi: 10.3389/fclim.2021.685227

55. Matthews, H.D., Zickfeld, K., Dickau, M. et al. Temporary nature-based carbon removal can lower peak warming in a well-below 2 °C scenario. Commun Earth Environ 3, 65 (2022). https://doi.org/10.1038/s43247-022-00391-z

CO$_2$RE THE GREENHOUSE GAS REMOVAL HUB

www.co2re.org

Funded through the UKRI SPF Greenhouse Gas Removal Demonstrators (GGR-D) Programme, CO_2RE co-ordinates the Programme and conducts solutions-led research to evaluate a balanced portfolio of economically, socially and environmentally scalable Greenhouse Gas Removal options, with associated policy design, engagement and outreach.

UK Research and Innovation

CO_2RE, The Greenhouse Gas Removal Hub is funded by UK Research and Innovation grant reference NE/V013106/1.