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Towards improved cost estimates for monitoring, reporting and verification of carbon dioxide removal

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Policy report

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Contents

Summary

Key messages

- Collecting detailed and accurate information on the cost of monitoring, reporting and verification (MRV) for carbon dioxide removal (CDR) is a challenge. Little information is publicly available, and companies find it difficult to share what information they have, because it is either commercially sensitive, unknown or difficult to disaggregate into constituent parts.
- Approaches to MRV are currently in a dynamic phase of iteration. Given the current unknowns and scope for continued research and development, the spectrum of MRV costs presented here are just a snapshot in time and are likely to change quickly.
- There are large variations in the cost of MRV within and between CDR methods. MRV can account for over 50% of costs for some techniques (e.g. ocean alkalinity enhancement, enhanced rock weathering and soil organic carbon) and up to 73% (for biomass sinking). For some methods, the cost of MRV could therefore be an important factor in determining long-run marginal costs of CDR.
- Not all CDR projects consider the cost of MRV to be a barrier to upscaling. Those that do typically have higher relative costs and relate to open-system marine CDR methods.
- Uncertainty about future government regulation and a lack of protocol standardisation are major barriers to assessing and reducing the cost of MRV. This is potentially a positive insight given most authorities are developing jurisdictional CDR and MRV guidelines.
- High operating expenses (OPEX), particularly those relating to labour costs for fieldwork and sampling, contribute significantly to the overall cost of MRV.
- Some uncertainty over quantifying net removal in MRV is inevitable. Where the incremental cost to reduce uncertainty is too high, the issuance of removal credits should be underpinned by conservative assumptions about the lifecycle emissions of a project and the risk CO_2 will be re-released. In part, this can be remedied by appropriate guardrails such as carbon insurance and buffer pool contributions.

High-level recommendations for the UK and other jurisdictions

1. The UK's Department for Energy Security and Net Zero (DESNZ) should prioritise harmonising MRV practices and principles in the UK with jurisdictions such as the EU and US and focus on developing common cross-jurisdictional MRV data collection and management practices in order to better facilitate interoperability and cross-jurisdictional comparisons. At the same time, the desire to standardise must not stifle innovation in MRV protocols. Protocols must be adaptable and flexible without enshrining standards that become outdated in a few years' time. This could be practically achieved by committing to semi-frequent review and consultation periods (e.g. every two to three years) and establishing working groups to build consensus views across the industry to ensure best available practice is reflected in MRV approaches.
2. Instilling greater transparency is a way to overcome information asymmetries that stymy market development and increase costs. Such transparency could be a precondition for receiving public funds. Additional support for expensive data-sharing infrastructure is needed in order to make large datasets or simulations publicly available and auditable.
3. To effectively reduce MRV costs, DESNZ should develop MRV support mechanisms that are adaptive and recognise the varying needs of different CDR processes by supporting MRV

cost reductions. This could be in the form of, for example, targeted capital expenditure (CAPEX) support for advanced sensors, remote sensing applications and AI-driven data verification. Such a mechanism could take the form of a dedicated CDR innovation fund. For labour-intensive CDR pathways, OPEX support is also required. OPEX and CAPEX support should be made available for the early years of project development which is where the majority of MRV costs fall, and then taper over time. All aspects of the MRV process should be digitalised, such that so-called digital MRV (dMRV) becomes the norm.

4. To enhance confidence and manage uncertainty over MRV, standard-developing organisations and jurisdictions should adopt conservative approaches to crediting, including considering if it is too premature to credit some methods today – especially where the incremental cost of MRV to reduce uncertainty is too high. This approach could also include the use of probabilistic certainty thresholds that are tailored to, and differ for, individual CDR methods based on their use cases. Conservative discounting and baselining in addition to conventional risk management approaches such as buffer pools should be considered.
5. DESNZ and other relevant agencies in the UK should develop a framework that allows MRV protocols to be graded based on their performance against the minimum standards described in Recommendation 1, to ensure a continuous high standard of quality and alignment with emerging market preferences for high-quality CDR. At the same time, the protocols must not be so complex that they present a barrier to achieving desired outcomes or so stringent that they make MRV prohibitively expensive. Where protocols are shown to be misaligned with UK best practice, MRV providers should be given time to rectify this, so that there is alignment with market demands and regulatory requirements. Ensuring adherence to a minimum standards framework could be fulfilled by an MRV regulator.
6. Economic approaches to valuing temporary storage should move towards method-specific MRV cost assumptions. This would be an important step forward, not least because it might change how the cost-effectiveness of temporary storage versus more durable CDR is currently perceived.

Accelerating carbon dioxide removal

To meet climate goals, as well as rapidly reducing greenhouse gas emissions, carbon dioxide will need to be removed from the atmosphere. This is implicit within net zero targets and legitimised by the need to compensate for residual (i.e. unavoidable) emissions. The proliferation of net zero targets, and by extension the rapid increase in demand for and deployment of carbon dioxide removal (CDR), has led to growing attention on the governance of CDR. A central component of the governance architecture for CDR is monitoring, reporting and verification (MRV).

Although there are differing views on the definition of MRV for CDR, such as whether the ‘M’ refers to ‘measuring’ or ‘monitoring’, for the purpose of this report we define MRV as the process of:

- **Measuring or quantifying net carbon dioxide (CO_2) and other greenhouse gas emissions removals** across the whole lifecycle supply chain of a CDR activity and continuing to monitor those net removals over the course of a CDR activity.
- **Reporting on those net removals, quantified relative to a baseline, through national inventory reports** under the UN Framework Convention on Climate Change (UNFCCC)/Paris Agreement or project registries to the Greenhouse Gas Protocol.
- **Verifying through an independent third-party the veracity of an emissions removal claim** by ensuring the relevant CDR standard has been followed. The greenhouse gas programme then certifies and issues carbon credits.

This report considers MRV only in relation to carbon accounting for CDR activities themselves, and not for other externalities e.g. increases in pollution or overuse of resources, or co-benefits such as improvements to air quality: while measuring these is important too, this aspect of MRV is beyond the scope of this report.

The importance of MRV for CDR

MRV helps governments, businesses and civil society to assess whether a given CDR project has achieved its claims and thus fulfilled the conditions of a given CDR standard's methodology document, resulting in CO_2 being stored durably and safely. Well-designed MRV can help these actors overcome information gaps and asymmetries that may be a barrier to making investment or regulatory decisions. It will build trust and confidence in methods of CDR where there might otherwise be hesitation over capital investment and speed up the integration of CDR into climate policy – and thus bolster the potential role CDR can play in mitigating climate change.

Why focus on the cost of MRV?

Although research on key themes relating to the governance of CDR include discussions on the role and importance of MRV, the costs arising from the development and implementation of MRV systems for CDR only receive a cursory discussion in the literature and in policy discussion. This is an important knowledge gap to fill.

If MRV remains expensive, efforts to reduce the overall cost of CDR over time will suffer. This is particularly important to overcome for those methods over which there is currently high uncertainty in relation to MRV but long-run scalability and the ability to store carbon durably. It is necessary to understand the extent to which MRV cost is a priority factor in determining the long-run marginal costs of CDR, and how costs can be reduced, by whom and in a way that does not compromise environmental integrity.

In the absence of data, early contributions to this field assume ongoing MRV costs are 5% of the total investment for all CDR. Beyond this estimate, the cost of MRV pertaining to specific CDR methods is hard to find. Current MRV is often proprietary and not visible beyond the company carrying out the CDR, with its costs bundled within overall cost estimates. This makes it difficult to highlight where there is uncertainty or risks in various approaches, or where higher MRV costs may pose a barrier to financing specific removal technologies.

As policymakers begin to design MRV standards it is important to strike a balance between acceptable cost, commercial needs and accuracy of quantifying removals. In striving to reduce uncertainties, for example relating to the lifecycle assessment requirements or verification of durable storage, the development and implementation of MRV for CDR could come with considerable additional costs. Current discussion is typically dominated by considerations of how to reduce uncertainty – e.g. through higher-accuracy remote sensing, fit-for-purpose models and greater use of in-situ measurements. It is important to broaden the discussion to include cost considerations which hitherto have been largely neglected. Understanding the incremental cost to quantify uncertainty will aid the design of policy that remains robust and flexible but not overly burdensome.

How much does MRV cost?

It is important to note that CDR is still a relatively nascent industry and approaches to MRV are in an iterative and dynamic phase. As diverse CDR companies scale up and MRV protocols continue to be developed, today's threshold for 'first of a kind' (FOAK) projects may be different than the threshold for 'n'th of a kind' (NOAK) projects. For example, data will be accumulated to develop and calibrate models (e.g. in the case of enhanced rock weathering [ERW]) and decay curves (e.g. to model the decay rate of biochar). The future cost of MRV could be lower if companies can leverage modelled predictions based on verified/measurable parameters rather than conducting expensive in-situ sampling.

Given this context, and how little data there is, the MRV costs presented here are just a snapshot in time, with the ability to compare costs further hindered by potentially different system boundaries (both temporal and spatial) and because counterfactuals likely differ within and across methods and jurisdictions. However, it provides a starting point to assess whether MRV costs are intrinsic to the method or are likely to change over time as science, policy and technology develop.

Figure S1a (next page) compares absolute MRV cost data (£/tonne) from a Grantham Research Institute survey of CDR developers and a Frontier dataset across 12 CDR methods. Figure S1b compares relative cost data (MRV cost/tonne as a percentage of total cost) from the same two datasets with the mean MRV cost presented as a percentage of the range of the total removal cost.

The charts illustrate the range and mean for each method. Where no range is presented, only a single datapoint exists. Frontier data exist for 2022, 2023 and 2024. The Grantham Research Institute data were collected in mid-2024. The sample sizes for each method are small, leading to wide ranges in cost estimates within and between methods. While this is not statistically significant, it remains useful for establishing a first set of cost estimates.

Although the focus on relative costs is important, as it can influence long-run CDR costs, high relative costs for methods with small absolute costs is less consequential, as is the case for ocean alkalinity enhancement (OAE). What matters is the total cost of CDR – and the extent to which this is driven by MRV – relative to other abatement technologies as this will drive investment decisions. In many cases the cost of MRV alone is significantly higher than the current cost of abatement in compliance markets such as the UK (£41/tonne) and the EU (£58/tonne) (figures from 2 September 2024).

Figure S1a. Absolute cost of MRV (£ per tonne of carbon)

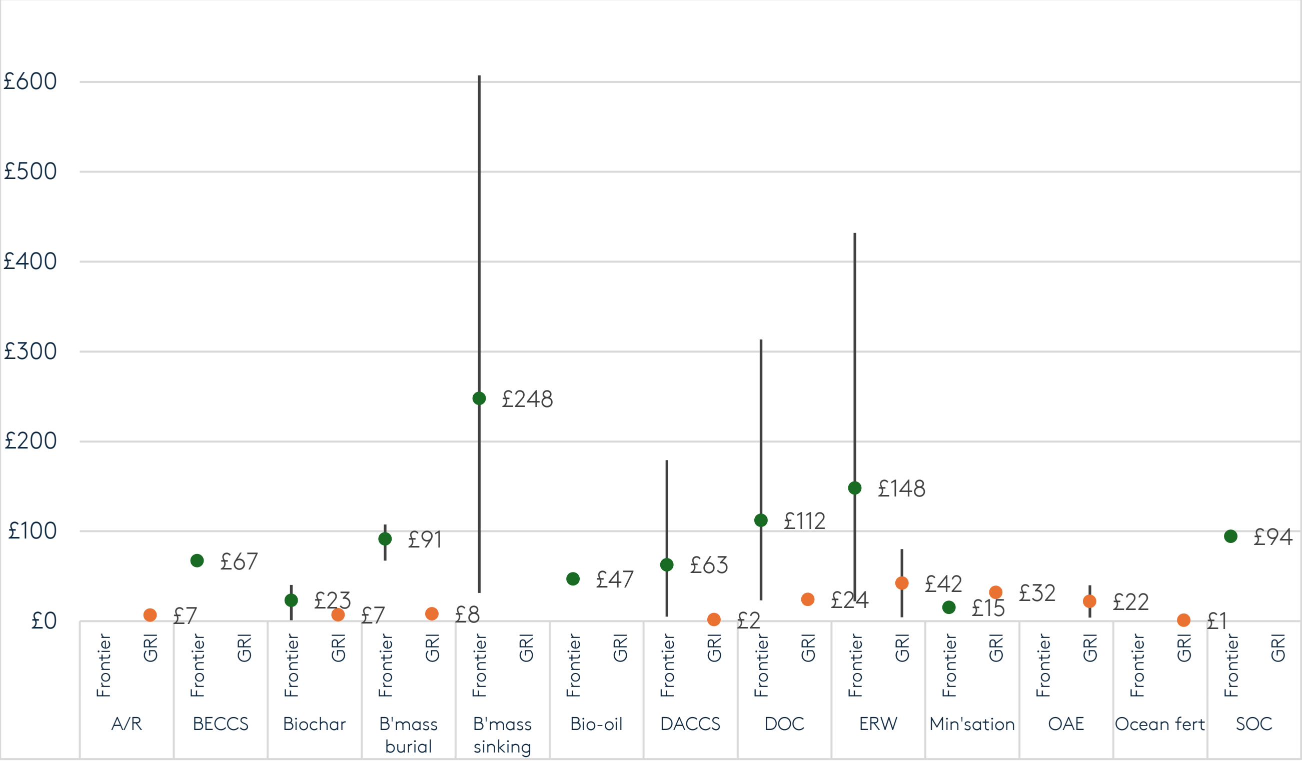
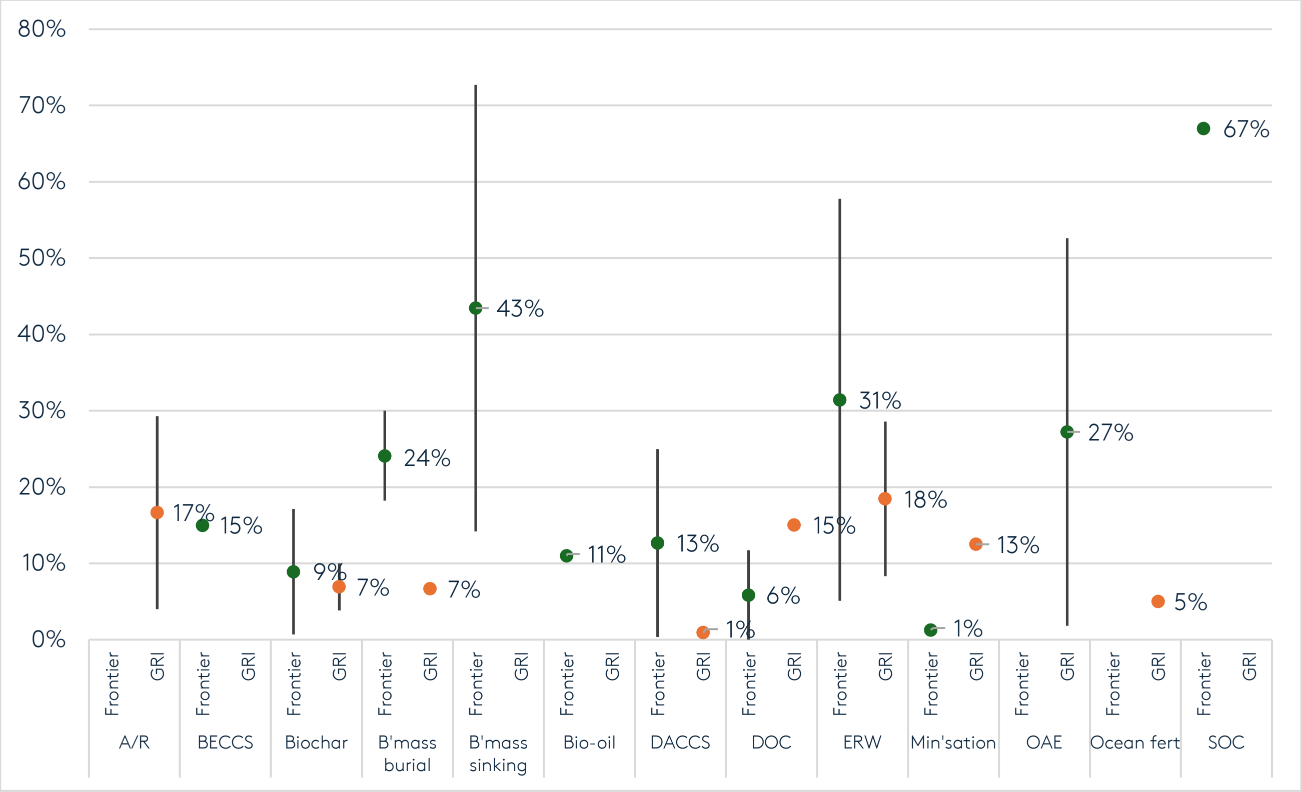


Figure S1b. Relative cost of MRV (% of total cost)



Notes and sources: two datasets are used and are presented in 2024 prices. Orange dots denote data collected from the Grantham Research Institute (GRI) survey. Green dots denote data from Frontier (Advanced Market Commitment request for proposal (RFP) agreements: https://github.com/frontierclimate/carbon-removal-source-materials/tree/main/Purchase%20Agreements*).*
A/R = afforestation and reforestation; BECCS = bioenergy with carbon capture and storage; b'mass – biomass; DACCS = direct air carbon capture and storage; DOC = direct ocean capture; ERW = enhanced rock weathering; Min'sation = mineralisation; OAE = ocean alkalinity enhancement; Ocean fert = ocean fertilisation; SOC = soil organic carbon.

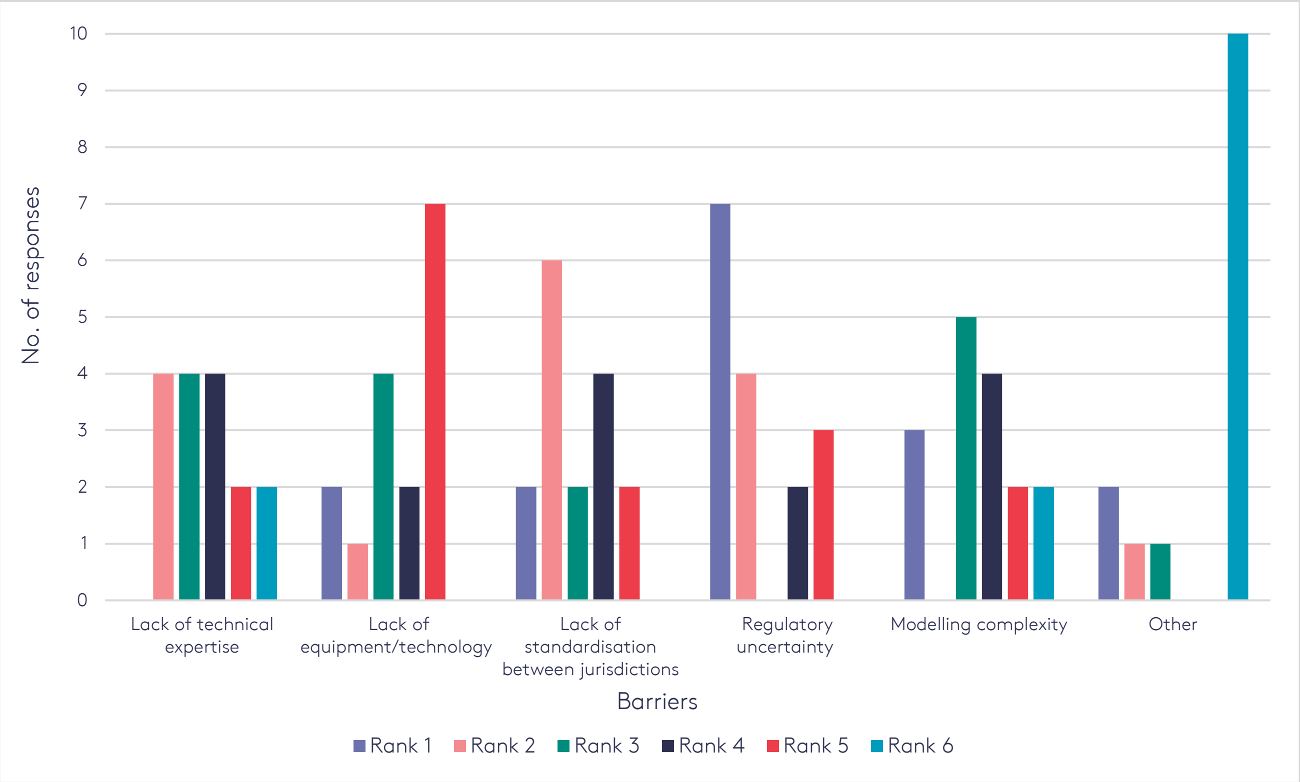
Is MRV cost a barrier to scaling up CDR?

The hypothesis of this research was that MRV would be considered a significant barrier to scaling up CDR. The Grantham Research Institute survey of CDR developers indicated mixed perceptions when respondents were asked: "*To what extent do you agree with the following statement: At present, the cost of MRV is a significant barrier to scaling?*" Twenty-eight per cent of respondents disagreed and 11% strongly disagreed that MRV costs are a significant barrier; only 18% strongly agreed.

The extent to which MRV cost is perceived as a barrier differs across methods. Respondents working on geochemical (e.g. ERW) and marine (m) CDR methods tended to view the cost of MRV as a bigger barrier to upscaling compared with those working on land-based biological CDR and chemical CDR (e.g. direct air carbon capture and storage – DACCS). For land-based biological methods, predominantly comprised of biochar, the majority of respondents disagreed that the cost of MRV is a big barrier to upscaling. Unsurprisingly, companies that disagreed or strongly disagreed had lower average relative MRV costs – 6.6% – as opposed to the 25.9% average cost for companies that agreed or strongly agreed with the statement.

Although the cost of MRV was not perceived as a big barrier to upscaling by operators of all CDR methods, it is still important to understand what the biggest barriers to reducing MRV cost are. Figure S2 illustrates the aggregate survey results. The height of the bars illustrates the number of times each barrier was ranked and the different colours represent their ranking placement.

Figure S2. Biggest barriers to reducing MRV cost, as ranked by survey respondents



Note: There were 28 respondents.

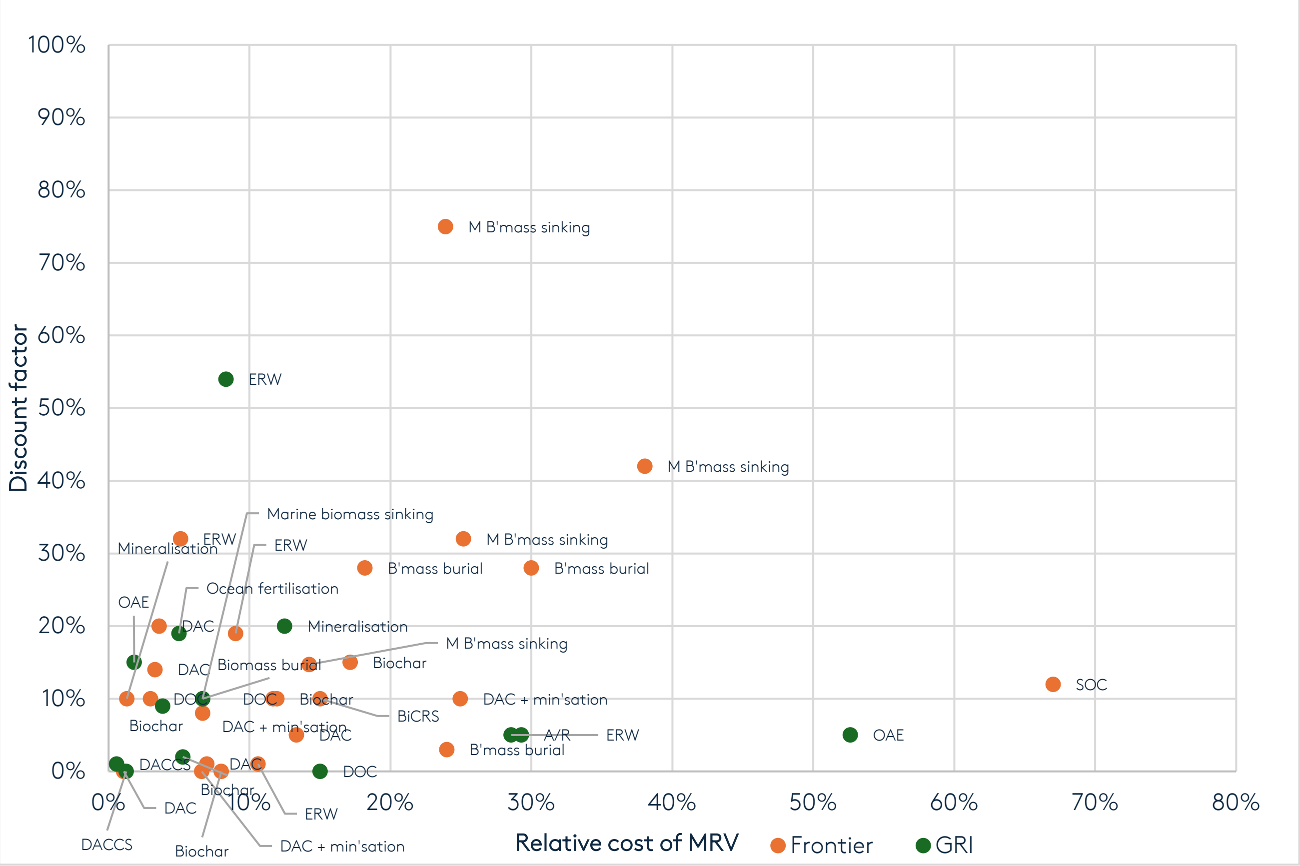
Across all methods, 'regulatory uncertainty' was ranked as the number 1 barrier to cost reduction the greatest number of times, followed by 'modelling complexity'. A 'lack of standardisation between jurisdictions' had the highest number of second rank votes. However, once CDR methods become established, the desire for greater standardisation and regulatory certainty may become an impediment to innovation.

Some barriers are specific to certain methods. For DACCS companies, the biggest barriers to reducing MRV cost were considered to be regulatory uncertainty and lack of standardisation, with a lack of equipment/technology and modelling complexity not considered to be significant barriers. Similarly, for biochar, regulatory uncertainty and a lack of standardisation were considered the largest barriers, and a lack of technology and equipment the smallest barrier. The picture was more mixed for OAE. Although regulatory uncertainty was again named as a big barrier for this method, a lack of technical expertise and modelling complexity were also barriers to reducing MRV cost. For ERW, modelling complexity was clearly perceived to be the biggest barrier and in contrast to other methods, regulatory uncertainty was considered a smaller barrier. For afforestation and reforestation (A/R) the picture was again quite mixed, with lack of equipment and regulatory uncertainty ranked as the biggest barriers, with a lack of standardisation and a lack of technical expertise also considered to be significant.

What is the relationship between MRV certainty and cost?

Figure S3 shows the relationship between MRV cost and the self-reported discount factor in the Frontier dataset and the certainty threshold requested in Grantham's survey. DACCS companies self-reported the highest average certainty threshold. Given the relative maturity of geological sequestration used for CCS (and associated protocols that underpin DACCS) and the fact that DACCS occurs in a highly contained environment, it can be expected that higher certainty is attainable. In contrast, ERW companies self-reported the lowest average threshold in the Grantham dataset and marine biomass sinking companies self-reported the lowest certainty threshold in the Frontier dataset. For these companies, this could reflect that calculating net removal is inherently more complex where system boundaries can be difficult to define and monitor. This is exemplified by ERW respondents who cite modelling complexity as the biggest barrier to MRV cost reductions. The analysis shown in Figure S3 indicates a mild causal relationship between the size of the discount factor and the cost of the MRV process. This is most apparent for the Frontier dataset.

Figure S3. Relationship between the relative cost of MRV and the discount factor used in both the Grantham Research Institute and Frontier datasets



Barriers to reducing MRV costs are predominantly a policy challenge

The barriers to reducing MRV costs have coalesced around a need for regulatory certainty and a lack of standardisation between jurisdictions. This is ostensibly a policy barrier and was found to be true across all CDR methods. This barrier is surmountable given that jurisdictions such as the EU and UK are developing jurisdictional CDR methodologies and standards which will provide policy certainty in the short to medium term.

However, not all jurisdictions are moving in parallel, which could add further complexity to an already complex regulatory environment. Collaboration and alignment between the EU, UK and US represent a substantial opportunity to align quality standards where the majority of novel and conventional removal activity is occurring and where demand is greatest. Ensuring buyers can easily make direct comparisons between projects assessed by the same protocol in different jurisdictions represents a significant opportunity to reduce costs as projects can align processes with a single MRV protocol.

Key innovations to reduce MRV cost

Our qualitative results provide more indication of what factors might reduce costs. The primary theme from the survey results in this respect was digitising and automating MRV. Respondents from various sectors highlighted the significance of automation, particularly in data verification and remote sensing for better measurement. Additionally, respondents highlighted a need for improved modelling and accuracy and investments in sensors and other monitoring innovations to drive down costs.

From the respondents that answered questions relating to a breakdown of operational and capital expenditures per tonne of CO_2 removed, all respondents indicated that OPEX was a large component of the total cost of MRV. This result implies a need for policies beyond traditional CAPEX support that cater to the varied characteristics and cost profiles of different CDR methods. Government support programmes can be an important lever in this regard. For example, the US, while not developing a national CDR quality standard, has made targeted investments to improve MRV processes for mCDR pathways through the SEA-CO2 programme to advance cost-effective MRV alongside a $15 million funding call by the Department of Energy to develop method-agnostic MRV best practice and technologies.

Getting comfortable with uncertainty

As some uncertainty related to the efficacy of CDR projects is inevitable, this raises the question of how to manage this uncertainty, including defining acceptable uncertainty bounds. To some extent this depends on the claims buyers of CDR want to make, which can change expectations about confidence in MRV quantification. Acceptable certainty thresholds may differ depending on the type of buyer and the use case of a purchase (i.e. whether a purchase will be used to claim one-to-one emission-removal compensation, or merely represent an investment). Catalytic buyers, for example, may accept lower certainty or quality if the intended purpose of purchased removals is for co-learning and stimulating demand. On the other hand, a higher certainty threshold may be required for companies that are buying CDR solely for compensatory claims.

Moving forward, confidence and credibility can be enhanced by establishing upper and lower uncertainty bounds for different use cases and adopting a conservative baselining approach for MRV. A probabilistic approach to dealing with uncertainty with regard to the efficiency of carbon capture and the risk of capture reversals, underpinned by statistical analysis of observations or model results, should provide bounds for real world outcomes, ensuring that credits are issued at a conservative probability level. This could differ for each method, with policymakers establishing higher bounds for methods with geological storage where MRV is comparatively less complex, and lower bounds for open system CDR such as OAE, where MRV is comparatively more complex.

Another key knowledge gap is in understanding the incremental cost of MRV to reduce uncertainty. While some innovations may yield large reductions in uncertainty at minimal cost, others may be too expensive to be economically viable (whereby the additional value from selling higher credit volumes does not outweigh investment costs). Our analysis indicates that some of the most uncertain methods are also the most expensive (e.g. ERW and marine biomass sinking). Where MRV is costly, complex or deficient, it may lead to trade-offs between accuracy and cost, particularly if there is insufficient willingness to pay for more accurate, but more expensive MRV.

Factors influencing approaches to MRV

Although cost is an important consideration, it was not seen to be the overriding factor. Respondents emphasised the need to balance the overall project budget with accuracy, indicating the need for a nuanced approach to MRV expenditure. For instance, while some noted that cost was the primary influence on their choice of MRV provider, others described a blend of requirements and budget considerations. There was also a recognition of the complexities involved with projecting MRV costs given how young so many of the companies are. As such, several respondents admitted lacking a full understanding of the costs.

Notably, some project developers professed to be seeking more extensive MRV than the current methodologies outline, driven by the quality preferences of buyers. This underscores the importance of aligning MRV practices with market demands. Additionally, the design and quality of standards and protocols were highlighted as crucial factors that define costs, reinforcing the need for robust frameworks to guide MRV processes.

Informing wider cost assumptions

Understanding the cost of MRV for different methods can also inform academic and policy research, by providing more accurate MRV costs within economic approaches for valuing temporary storage (e.g. forests need to be replanted/maintained as carbon is only stored temporarily for less than 100 years). Early contributions to this field assume ongoing MRV costs are 5% of the total investment for all CDR. However, MRV costs vary across methods, and in almost all cases significantly exceed this number. The average MRV cost across all methods relative to the total cost of removal for the Grantham dataset is 12%, while for the Frontier data set it is 23%.

Using more accurate MRV and method-specific cost information will substantially change the equivalency ratio that is used to determine the number of temporary tonnes of removed carbon needed to be stored to be equivalent to 1 tonne stored permanently. This will result in a higher ratio of temporary CDR to permanent CDR. Consequently, what appears to be ‘cheaper’ removal today actually implies large future costs when the higher costs of MRV are fully accounted for.

With governments such as the UK’s considering this approach, it is critical that the assumptions are robust. Small differences in assessing MRV costs alongside normative assumptions about the social cost of carbon and future discount rates or future removal costs can imply dramatic environmental and economic implications for society.

Beyond this, MRV cost estimates are helpful for policymakers when assessing whether specific support for MRV should be included within CDR policy frameworks such as the forthcoming Carbon Contracts for Difference within the ‘UK GGR Business Model’. This research suggests that this might not be necessary for the first iteration of ‘UK GGR business models’, which prioritise CCS-enabled CDR such as DACCS and BECCS, where the cost of MRV is neither a barrier to upscaling nor particularly high. However, if and when the business model is broadened to include CDR methods where the absolute and relative cost of MRV is higher (such as ERW or mCDR), explicit provisions to support MRV cost may need to be included. It is important that the business model is flexible enough to accommodate this in the future.

1. Introduction

Alongside actions to rapidly reduce greenhouse gas emissions, carbon dioxide will need to be removed from the atmosphere if the world is to meet the Paris Agreement climate goals. The proliferation of net zero targets, and by extension the use – or planned use – of carbon dioxide removal (CDR), has led to increased attention on the governance of CDR (Lezaun et al., 2021; Bellamy et al., 2021; Burke and Schenuit, 2023; Edenhofer et al., 2023). Monitoring, reporting and verification (MRV) is a central component of the governance architecture for CDR.

This report examines the cost of MRV for different CDR methods, the extent to which the cost of MRV for different methods is perceived as a barrier to their upscaling, where opportunities lie to reduce the cost of MRV and what factors influence the choice of MRV protocol. It provides recommendations for the UK government but which are more widely applicable.

How much carbon dioxide removal is necessary?

To reach net zero CO_2 emissions by 2050 and limit global warming to 1.5 C with no or limited overshoot by 2100 and net negative emissions thereafter, it is forecast that between 100 and 1,000Gt (giga/billion tonnes) of carbon dioxide removal (CDR) is needed over this century (IPCC, 2022). This is implicit within net zero targets and legitimised by the need to eliminate 'residual' emissions – i.e. those that are very difficult to abate. The required reliance on CDR in 1.5°C pathways raises questions about how to prioritise the temporal distribution of CDR as opposed to conventional abatement, what methods to prioritise (including through research and development [R&D] and policy mechanisms) and how rapidly to upscale near-term CDR.

To answer these questions it is important to ascertain what constitutes a 'legitimate' amount of residual emissions. For Annex 1 countries to the UN Framework Convention on Climate Change (broadly speaking, industrialised countries), estimates of residual emissions average between 18% (Smith et al., 2024) and 21% (Buck et al., 2023) of their peak emissions. These emissions are typically related to aviation, long-distance transport, structural materials, heavy industry, and baseload electricity (Mercer and Burke, 2023). However, the level of unabated emissions that are considered 'acceptable' and thus 'residual' is not agreed and is contingent on varying values, norms and interests (Lund et al., 2023).

The role of monitoring, reporting and verification (MRV)

Although there are differing views on the definition of MRV for CDR, such as whether the 'M' refers to 'measuring', 'monitoring or 'modelling' (Lebling et al., 2024), for the purpose of this report we define MRV as the process of:

- **Measuring or quantifying net carbon dioxide (CO_2) and other greenhouse gas emission removals** across the whole lifecycle supply chain of a CDR activity and continuing to monitor those net removals over the course of a CDR activity.
- **Reporting on those net removals, quantified relative to a baseline, through national inventory reports** under the UNFCCC/Paris Agreement or project registries to the Greenhouse Gas Protocol.
- **Verifying through an independent third-party the veracity of an emissions removal claim** by ensuring the relevant CDR standard has been followed. The Greenhouse Gas Protocol then certifies and issues carbon credits.

This report considers MRV only in relation to carbon accounting for CDR activities themselves, and not for other externalities that CDR might bring about, e.g. an increase in pollution or overuse of resources, or co-benefits such as improvements to air quality. However, the importance of measuring and accounting for wider co-benefits and externalities beyond just carbon removal and storage is acknowledged – it is simply not within the scope of this report.

Robust MRV systems can help governments and private sector actors overcome information gaps and asymmetries that may be creating barriers to investment or regulatory decision-making. These issues may erode trust and confidence in CDR, halt capital investment and slow down the development of CDR as well as the integration of CDR into climate policy (Macquarie, 2022). Indeed, a recent study on policy support for bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS) in Europe found that in terms of regulatory levers, carbon accounting and MRV stood out as preferred policy interventions for 78% of industry respondents, ranked above liability rules, citizen assemblies and regulatory standards among others (Yang et al., 2024).

In summary, MRV is integral to:

- **Assessing whether a given CDR project has done what has been claimed**, i.e. it has followed the relevant methodology that dictates the system boundary of a project, the lifecycle analysis process, and the monitoring process for durable storage (Schulte et al., 2024). Enacting MRV also enables jurisdictions to account for removals within their national greenhouse gas inventories or nationally determined contributions (NDCs).
- **Enabling CDR to be integrated into climate policies, targets and markets.** Crediting CDR via MRV processes, depending on the goal or incentives underpinning the CDR project, transforms the removed carbon into a tangible commodity for which project developers can seek payment through either the voluntary carbon market or government-funded subsidies.
- **Providing accountability and oversight for market participants and governments, and importantly, for the general public** to have oversight of CDR operations and hold project developers to account for their climate, public health and environmental impacts, for example via civil litigation and during processes for seeking planning approval.
- **Supporting conditions to allow liability for stored CO_2, for example in subsurface aquifers or CO_2 pipelines, to be transferred between different actors.** For CDR to scale up, project developers need to understand where their liabilities begin and end in order to smooth the transaction process and provide recourse in the event of reversals (i.e. when sequestered carbon escapes back into the atmosphere) by evidencing which entity is responsible for ‘making good’ on escaped CO_2.
- **Driving investment into early- to mid-stage CDR startups through improving transparency and ease of analysis** to better understand outstanding research questions and other unresolved uncertainties for theoretically promising CDR methods such as ocean alkalinity enhancement (OAE), in order to better inform policy development.

Guidance from the Intergovernmental Panel on Climate Change (IPCC) on greenhouse gas quantification exists for activities based on REDD+ – i.e. ‘reducing emissions from deforestation and forest degradation in developing countries’ – and by extension some conventional CDR methods. However, guidance for novel CDR methods is generally lacking, other than for BECCS and biochar (where carbon waste from agriculture is ‘charred’ and buried, to lock up its carbon in the soil). Box 1.1 below outlines conventional and novel CDR methods.

Until recently, MRV development for novel CDR methods has occurred in the voluntary carbon market (VCM) and at the project level. A recent development at the supranational level is the development, by the IPCC, of a methodology report for novel carbon removal methods (beyond those that already exist for land use, land-use change and forestry [LULUCF]) alongside refined guidance on carbon capture and storage (CCS) and carbon capture and utilisation. It is understood that the report, which is due to be published in 2027, will provide guidance for including novel CDR in national inventories and guide best practice in the VCM (Schulte et al., 2024).

Box 1.1. Conventional and novel methods of carbon dioxide removal (CDR)

Conventional methods

This category encompasses CDR methods that are well established, already deployed at scale and widely reported by countries as part of land use, land-use change and forestry (LULUCF) activities. The methods included in this group are:

- Afforestation/reforestation (A/R)
- Agroforestry
- Forest management
- Sequestration of soil organic carbon (SOC) in croplands and grasslands
- Peatland and coastal wetland restoration
- Durable wood products.

Novel methods

This category encompasses all CDR methods not considered 'conventional'. With these methods the captured carbon is stored in geological formations, the ocean or products. These methods generally have a lower level of readiness for deployment and are therefore currently deployed at smaller scales than the conventional methods listed above (see further Section 3). Examples of such methods include:

- Bioenergy with carbon capture and storage (BECCS)
- Direct air carbon capture and storage (DACCS)
- Direction ocean capture (DOC)
- Enhanced rock weathering (ERW)
- Biochar
- Mineral products
- Ocean alkalinity enhancement (OAE)
- Ocean fertilisation (OF).

Open-loop systems are interventions in natural biogeochemical processes to stimulate CO_2 removal – e.g. OAE.

Closed-loop systems are those where CO_2 is drawn down from ambient air through approaches that capture, isolate and store captured CO_2 – e.g. DACCS.

See Table 3.1 for a further categorisation into biological, geochemical and chemical capture processes and Section 4 of Mercer and Burke (2023) for a description of how the main CDR processes work.

Significant challenges in MRV remain for both conventional and novel CDR methods. The tools, instruments and protocols used to measure removals vary significantly for different methods and carbon accounting approaches are inconsistent in their handling of issues such as measurement of uncertainty, storage duration and lifecycle emissions (Schulte et al., 2024). Typically, verification processes only assess if protocols have been adhered to and not whether they are appropriate to ensure positive outcomes for the atmosphere. Moreover, in the absence of regulated supranational guidelines, regulatory efforts are developing in tandem with fast-moving, and often competing, developments in the VCM. Consequently, the MRV ecosystem has become increasingly crowded, with overlapping MRV protocols for some CDR methods and little coverage for others (Mercer and Burke, 2023; Arcusa and Hypolite-Sprenkle, 2022).

The importance of MRV costs

The ability for CDR companies to innovate and scale up is contingent on many factors, including incentives for deployment, the presence of markets and public acceptance of CDR, in addition to demand-pull policies to provide stable revenue streams (Nemet, 2018). These factors will influence the cost per tonne at which companies are able to deliver removal. This is important when considering the viability of companies and their ability to raise funds and remain competitive in an increasingly crowded marketplace. Companies that can successfully drive down costs to deliver removals will be more competitive and resilient than their peers that have costlier operations. However, as the CDR industry is so nascent, there remain many unknowns (across all pathways) in terms of what techniques and instruments will prove to be best practice and which method-specific approaches will be most competitive (in cost terms). For CDR to be upscaled, there is a need to bolster the transparency, availability and sharing of data so that collectively, CDR pathways can coalesce around the most effective techniques and practices, including in terms of MRV.

Some CDR methods are easier to monitor and verify than others and thus benefit from lower MRV costs – whether related to the existence of instrumentation for monitoring, or a pre-existing evidence base upon which to develop a CDR project. On the other hand, if MRV remains expensive – particularly if it represents a high relative share of the total cost – this could hamper efforts to reduce the cost of CDR over time. Hence, it is important to understand the extent to which MRV cost is an important factor in determining long-run marginal CDR costs, and if so, how the cost can be reduced, by whom and in a way that does not compromise environmental integrity.

Relevance to policymakers

These considerations are relevant for jurisdictions that are directly funding and incentivising CDR as part of their climate mitigation strategies. Governments patently need to understand whether their direction of funding represents good value for public money, i.e. whether projects are genuinely removing carbon and how cheap they are relative to other mitigation policies – including across different CDR pathways. Governments also need to have information on CDR costs in order to make important decisions about which CDR methods to incentivise and how much to fund R&D for MRV. Hypothetically, high-cost CDR might be expected to receive more public deployment support (this is evidenced in the US by the direct air capture hubs instituted under the Inflation Reduction Act [IRA]), whereas low-cost, deployment-ready methods could be expected to be funded through polluter pays approaches such as compliance mechanisms or the VCM.

Beyond value for public money there are other questions relating to which aspects of a removal process are eligible for public funds. The absolute and relative cost (i.e. the cost as a percentage of total costs) of MRV will vary between technologies and in some jurisdictions – such as the UK – it has yet to be determined if and to what extent MRV will be an eligible cost under public support programmes. Typically, only capital and operational expenditure (CAPEX and OPEX) associated with the construction and operation of facilities is considered. Some methods are potentially at a disadvantage if the related MRV is complex and costly, and are therefore not included within public support programmes.

While there are estimates available of the anticipated total cost of different CDR methods, the cost of MRV pertaining to specific CDR methods is hard to find. Current MRV is often proprietary and not visible externally, with its costs bundled within overall cost estimates. This makes it difficult to highlight where uncertainty or risks exist in various approaches or where higher MRV cost may pose a barrier to financing specific removal technologies.

Policymakers are beginning to design robust MRV systems and standards that are prioritising the development of CDR standards and guidelines, for example in the EU and the UK (see the EU's 'carbon removals and carbon farming' – CRCF – regulation [European Commission, n.d.] and the UK's business model design for greenhouse gas removals and BECCS [DESNZ, 2023]). As they do so, it is critical that they strike a balance between acceptable cost, commercial needs and accuracy of quantification: even though the CDR industry is at an early stage of development, some methods are at a disadvantage because of in-built characteristics that present varying challenges to overcome.

For example, with OAE, air-sea gas exchange and resultant quantification of net removals in an open loop system (see Box 1.1) requires substantial investment in sensors for data collection, modelling and MRV, whereas for conventional CDR, there is an extensive literature and well established field-based and geospatial/remote-sensed MRV options.

Such considerations are relevant given the need to support the viability of higher uncertainty open-loop systems – such as OAE – that have potentially substantial advantages in terms of long-run scalability, durability and thermodynamic efficiency (enhancing pre-existing natural carbon fluxes can be more efficient, cost-effective and scalable) over more precise, but costly closed-loop CDR methods. Where MRV engenders more uncertainty, it becomes more complex and costly. This could be compounded if MRV policies and protocols strive for unattainable levels of certainty.

Balancing cost and accuracy

Like any system, an MRV system is subject to uncertainties. These uncertainties can be due to incomplete foundational knowledge (i.e. the totality and quality of scientific evidence relating to the method), limited instrumentation or various sources of human error, including errors in classifying remote sensing imagery (Tokola, 2015), sampling errors, measurement and mapping errors (Plugge et al., 2011), and errors in models that predict the efficiency of different CDR methods.

In striving to reduce uncertainty, the development and implementation of MRV for CDR could come with considerable additional costs. The current discussion is typically dominated by considerations of how to reduce uncertainty through higher accuracy remote sensing, fit-for-purpose models and greater in-situ measurements; it is important that this is broadened to include cost considerations which hitherto have been largely neglected. Understanding the incremental cost to quantify uncertainty and incentives to reduce this uncertainty will aid the design of policy that remains robust and flexible but not overly burdensome. Resolving these issues is technical and may deter political and financial support. However, it is essential to advance MRV and design business models that enable a wide portfolio of CDR to be deployed to support the diversity of risk and benefit contained in each CDR method (Nemet, 2018).

Where the cost of MRV is prohibitive, policymakers may also consider what trade-offs they are willing to make, and what support is available, including support for R&D and demonstration to reduce costs for expensive MRV processes. Policymakers are beginning to recognise this challenge, making some public funds available. For example, in the US in 2023 the Department of Energy's Office of Technology Transitions, in partnership with the Office of Fossil Energy and Carbon Management, announced a funding programme that aims to support the development of MRV tools and protocols that are necessary to enable CDR commercialisation at scale (U.S. Department of Energy, 2023). In the absence of widespread public support, private grants – via philanthropic institutions or foundations – have been made available to advance MRV R&D and best practice (Carbon x, 2024), but not on an extensive scale.

What this report adds to the literature and CDR policy development

Although research on key themes relating to the governance of CDR includes discussions on the role and importance of MRV (e.g. Thorsdottir et al., 2024), the costs arising from the development and implementation of MRV systems for CDR only receive a cursory mention in the literature or in policy discussion. Previous research has typically focussed only on MRV costs within carbon pricing schemes (Bellassen et al., 2015) or on remote sensing technologies and field assessments for conventional terrestrial CDR such as afforestation (Hardcastle and Baird, 2008; Kohl et al., 2020). Understanding the cost of MRV for different methods can also inform academic research related to the fungibility of CDR methods, by providing more accurate MRV costs within economic approaches for valuing temporary storage, such as the Climate Repair Value approach developed by Prado and Mac Dowell (2023).

Overall, as the CDR industry is still nascent, the limited focus on MRV cost is perhaps not surprising, since for many companies, especially those using novel methods, the exact measurement, modelling and registry costs are still in flux and will not be known in detail until protocol and registry partners are selected. Nevertheless, it remains important to establish a baseline of relevant cost information across all methods. As the industry grows, this will enable researchers and policy practitioners to highlight differences between methods, observe how these change over time as companies scale up and technology advances, and develop a cost curve. All of this can inform both academic and public policy discussions.

Aims of this research

Using survey data and expert insights from CDR companies, the quantitative and qualitative analysis presented in this report examines the cost of MRV for different CDR methods, the extent to which companies using different methods perceive the cost of MRV as a barrier to upscaling, where opportunities lie to reduce MRV cost and what factors influence the choice of MRV protocol.

Using this information the report seeks to:

- Establish an MRV cost baseline for different CDR methods, in both absolute terms (£/tonne) and relative terms (as a percentage of the total CDR cost)
- Assess whether specific support for MRV should be included within CDR policy frameworks
- Understand how MRV cost and stringency can be balanced
- Inform MRV cost estimates for economic assessments for the time value of carbon
- Make recommendations for how governments can manage trade-offs relating to the cost versus accuracy of method-specific MRV approaches so that a diversity of CDR pathways remain viable.

Results from this study bring a new perspective on the development and cost implications of MRV systems.

The report is organised as follows:

- Section 2 outlines our methodological approach, including limitations.
- Section 3 describes the quantitative and qualitative results.
- Section 4 discusses the implications of the results and areas for further research.
- Section 5 concludes.

2. Methodological approach

Overview

Our primary method of data collection was via a survey of CDR suppliers. To design the survey, eight pilot interviews were held first with selected CDR experts and companies, using a semi-structured interview format. These key informants were targeted to represent a broad swathe of CDR methods.

The pilot interviews tested the first iteration of our survey to assess the viability and pertinence of the proposed questions. The survey questions were refined in accordance with the feedback from the pilot interviews, for example by incorporating more open-ended questions. All information from the surveys was anonymised to encourage participation and then aggregated. The survey did not ask for the name of the specific CDR company or individual. No identifying information will be published.[1]

Dissemination and response rate

Using publicly available information, a stakeholder mapping exercise was conducted that identified 65 CDR companies to survey. The companies were chosen because they had previously disclosed public information on their approach to MRV and potential costs through the Frontier advanced market commitment call for applications on the GitHub repository. Applicants that had provided MRV cost information in spring and autumn 2022 and summer 2023 were approached. In addition, the survey was shared with trade associations representing all the major CDR methods, who then disseminated the survey to their members. In total, there were 58 responses, although only 19 of the responses provided full and complete data that could be used right across the analysis.

Limitations

While utilising a survey to gather information provides valuable insights, several limitations need to be acknowledged. One major limitation was the reliance on self-reported costs. Without the ability to independently verify the legitimacy or operational status of the responding companies, the survey was reliant on the accuracy of the self-reported costs, with no option to test the veracity. In an attempt to mitigate this, the dissemination of the survey was controlled by directly approaching CDR companies and disseminating through trade associations, but this does not entirely eliminate the risk of receiving data from non-operational or illegitimate entities or the survey being conducted by a non-expert within the companies that responded. Additionally, the boundaries of what respondents considered to be within scope of the CDR process were not a required input.

An additional challenge encountered was that not all of the CDR companies responded to the survey request after initially showing interest during key informant scoping calls and providing input into the survey design. Another limitation was the complexity of sections of the survey relating to specific costs attributable to each of the MRV steps and detailed breakdowns of CAPEX and OPEX estimates. Many respondents considered these questions commercially sensitive and did not supply data as a result. The small response size was a significant limitation; however, this is a common issue in newly emerging industries like carbon removal. The anonymised nature of the survey further complicated the situation, as it prevented follow-up inquiries that could have helped clarify ambiguous responses or provide additional context, particularly concerning the boundaries and supply chains of the reported costs.

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[1] Ethical approval for this project was granted by the London School of Economics' Ethics Committee (no: 355670), in accordance with Economic and Social Research Council guidelines. Consent was granted at the beginning of the survey and no monetary remuneration was provided for participants to prevent potential biases, perceptions of unfairness, and undue influence.

3. Results

Table 3.1 provides an overview of the CDR methods that were included in a list for survey respondents to self-select.

Table 3.1. CDR methods included in survey

CDR method	Carbon capture process
Afforestation/reforestation	Biological
Agroforestry	Biological
Improved forest management	Biological
Peatland and wetland restoration	Biological
Coastal wetland management	Biological
Soil carbon sequestration in croplands and grasslands	Biological
Durable wood products	Biological
Biochar	Biological
Bio-oil storage	Biological
Bioenergy carbon capture and storage	Biological
Biomass burial	Biological
Ocean fertilisation	Biological
Marine biomass sinking (terrestrial and aquatic biomass)	Biological
Enhanced rock weathering	Geochemical
Mineralisation	Geochemical
Ocean alkalinity enhancement	Geochemical
Direct ocean capture	Chemical

Note: Respondents could also input an 'other' category.

Quantitative results

Characteristics of respondents

Table 3.2 below provides counts of the GGR methods represented in our sample. Figure 3.1a then provides an overview of the respondents to the survey and categorises them by self-reported technological readiness level (TRL) and years of operation. Within the research sample, six respondents were at TRL 9 (the highest level of readiness), four at TRL 6, three at TRL 5 and two at TRL 4. No respondents were recorded below TRL 4, potentially reflecting the survey strategy of approaching established CDR companies and sharing the survey through trade associations. Interestingly, nearly half of the 19 respondents (nine) had been in operation for less than a year at the time of the survey. These companies were clustered between TRLs 4 and 7.

Table 3.2. Count of respondents by CDR method

Biomass burial – 1 Marine biomass sinking – 1 Mineralisation – 1 Ocean fertilisation – 1	Afforestation/reforestation – 2 Enhanced rock weathering – 2 Direct air carbon capture – 2 Direct ocean capture storage – 2 Ocean alkalinity enhancement – 2 Multiple methods identified* – 2	Biochar – 3

*Note: *'Multiple methods identified' refers to two providers who provide MRV services to numerous CDR methods. Average costs were given across these methods and as such, this cost information is not presented in Figure 3.3 or 3.4.*

Figure 3.1a. Years in operation of respondent companies and their technological readiness level (TRL)

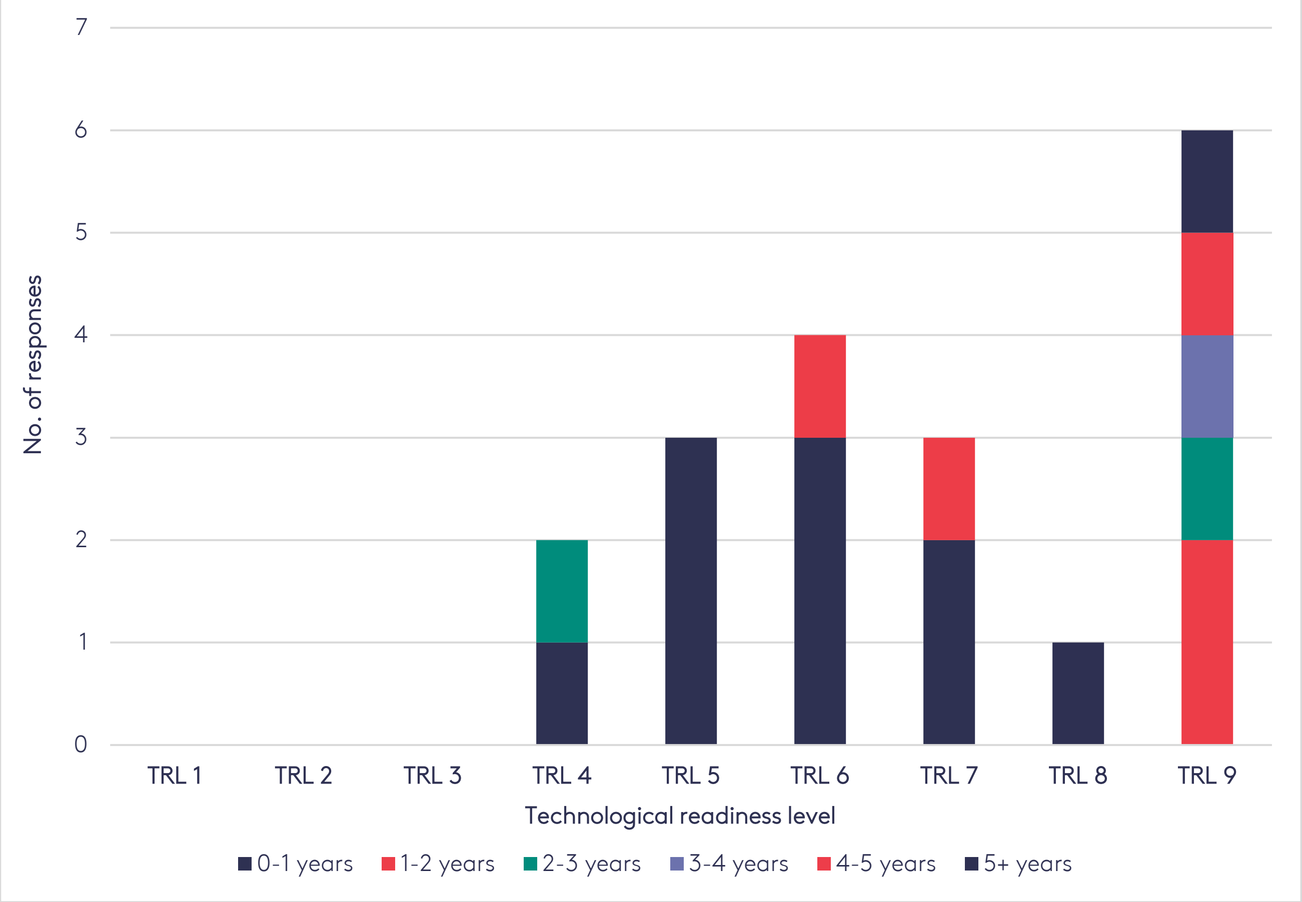
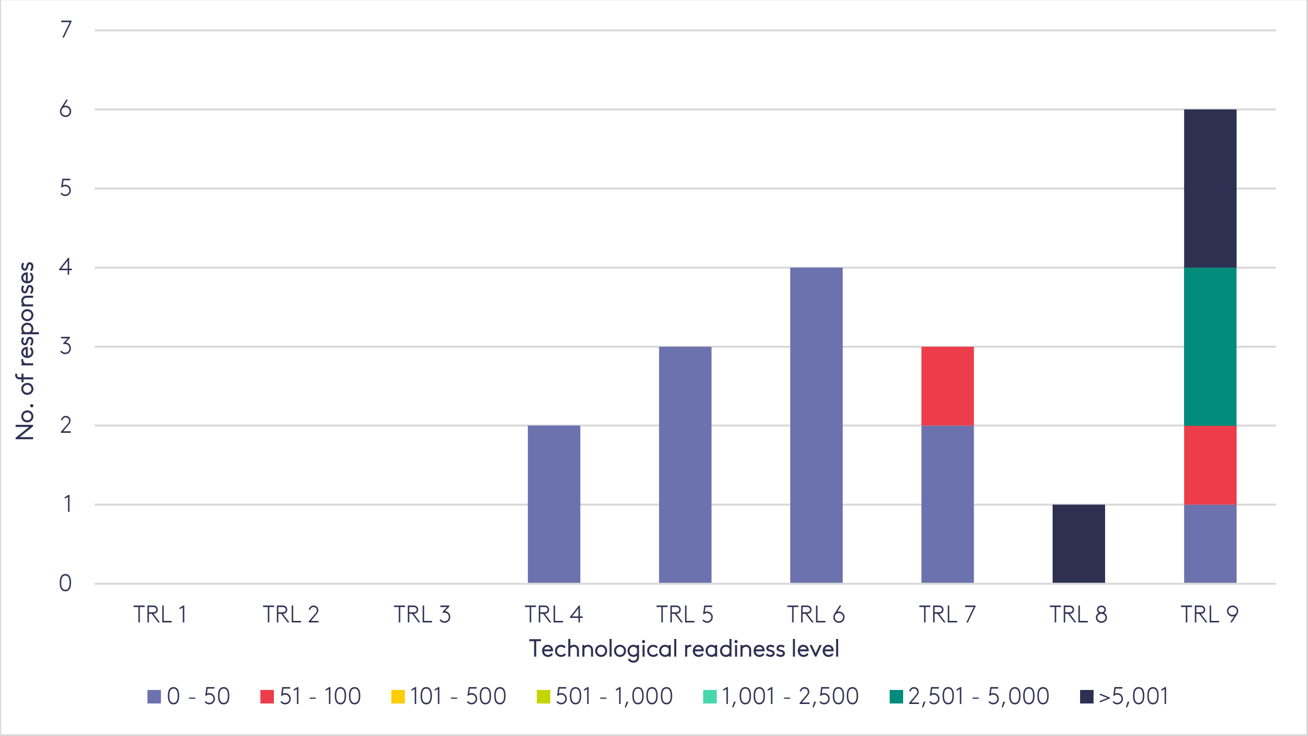


Figure 3.1b below provides a breakdown of reported yearly tonnes of carbon removed and TRL level. Those companies at lower TRLs (4–7) have only removed 0–50t/annum and unsurprisingly a causal relationship is indicated between technological readiness and tonnes removed. Two respondents reported removals in excess of 5,000t/annum and these were at TRLs 8 and 9.

Figure 3.1b. Yearly tonnes of carbon removed, by TRL level of companies



Cost of MRV

First, the absolute and relative cost of MRV across 12 CDR methods is presented. As the sample size from the survey was small, MRV costs found in the grey literature (specifically data from the Frontier advanced market commitment request for proposal [RFP] agreements) have been included as a comparison. Figure 3.2a compares absolute MRV cost data (£/tonne) from the Grantham Research Institute (GRI) survey and the Frontier data. Figure 3.2b compares relative cost data (MRV cost per tonne as a percentage of total cost) from the same two datasets with the mean MRV cost presented as a percentage of the range of the total removal cost. The charts illustrate the range and mean for each method. Where no range is presented, only one data point exists. The Frontier datasets for the years 2022 and 2023 have been combined, as the 2023 dataset is particularly small with poor coverage across CDR methods. An average has been calculated for the combined years and adjusted for inflation, with MRV costs presented in 2024 prices to enable comparison with the Grantham Research Institute's dataset for 2024.

Figure 3.2a highlights substantial heterogeneity among the absolute MRV costs across the Grantham and Frontier datasets. The highest range is for marine biomass sinking, with a high absolute cost figure of £607, a low figure of £31 and an average of £248 MRV/tonne (Frontier data). The next highest average figures are for direct ocean capture (DOC) at £112 and ERW at £148 (Frontier data). A/R had the smallest range with a high and low-cost estimate of £7 and £6 respectively (Grantham data). The lowest average MRV cost is £2/t for DACCS (Grantham data), which is substantially lower than the £63/t for DACCS seen in the Frontier data. With few exceptions, the average cost estimates from Grantham were lower than those from Frontier. Average costs are closest across the two data sets for biochar, where Frontier's cost is £23 and Grantham's is £7. The largest disparity occurs with DOC, where Frontier has an average cost of £112 and Grantham (with only one data point) registers £24.

The relative MRV costs in Figure 3.2b exhibit markedly less heterogeneity than observed for the absolute MRV costs in Figure 3.2a. The highest relative MRV costs across both datasets is 67% (for SOC – Frontier) with marine biomass sinking (Frontier data) providing the second highest, at 43%. Relative MRV costs are closest across the two datasets for biochar, with Frontier's costs being 9% and Grantham's 7%. The largest range of relative costs is found once again for marine biomass sinking with a high and low of 72.7% and 14.2% (Frontier data). The next highest spread is for OAE (Grantham data), with high/low figures of 52.6% and 1.8%. CDR methods that have a narrow range of relative costs include DACCS and biochar (both in the Grantham data).

High absolute MRV cost does not always translate to high relative cost. This is the case for technologies where the total cost of carbon removal remains particularly high. For example, DOC (Frontier data) has an absolute cost of £112/tonne, but this only represents 6% of total costs. In most cases, however, higher absolute costs generally translate to higher relative costs, as illustrated by SOC, biomass sinking and ERW. For methods starting from a lower average absolute cost per tonne, such as A/R, even relatively small MRV costs represent a relatively high proportion of total costs. ERW, OAE and biomass sinking have the greatest range of relative costs, which might be explained in part by the lack of a standardised approach for these novel methods. Biochar has relatively low absolute and relative costs due to the lack of need for long-term monitoring, with these two datasets having the closest similarity.

The average MRV cost relative to the total cost of removal in the Grantham dataset is 12%, while for the Frontier data set it is 23%. There are several possible explanations for this difference. First, there may be differences in the scale of the companies within the respective datasets. For example, the participants in the Grantham survey may be operating at a bigger scale, in terms of tonnes removed and credit issuance, which could result in some amortisation. Alternatively, if the projects in the Grantham dataset are operating at a smaller scale, the lower average relative MRV costs might result from underestimating costs. Lower volumes might give low estimates from overly optimistic assumptions that are not borne out when a project is scaled up and generates more data. When examining the data, the majority of Frontier projects sit at the lower end of the TRL distribution, between TRLs 3 and 6. In contrast, the majority of Grantham projects sit at the higher end of the TRL distribution, between 6 and 9. The Grantham dataset shows that higher TRL companies are removing more tonnes of carbon per annum than lower TRL companies. This may give credence to the former explanation, although given the limited amount of data, it is difficult to say definitively.

Second, the Frontier dataset holds project cost data from three different tranches (autumn [fall] and spring 2022, summer 2023 and summer 2024). Frontier's datasets for 2022 and 2023 reflect costs between one and two years earlier than the survey period for Grantham's dataset. The data from the earlier years has been adjusted for inflation so comparisons can be made in 2024 prices. Nevertheless, the intervening years may have seen reductions in costs for various capital expenditures related to MRV (e.g. for sensors, flow meters and certain modelling approaches) and also key questions being resolved and common practice updated as a result. This is explored in Section 4.

Figure 3.2a. Absolute cost of MRV (£ per tonne of carbon)

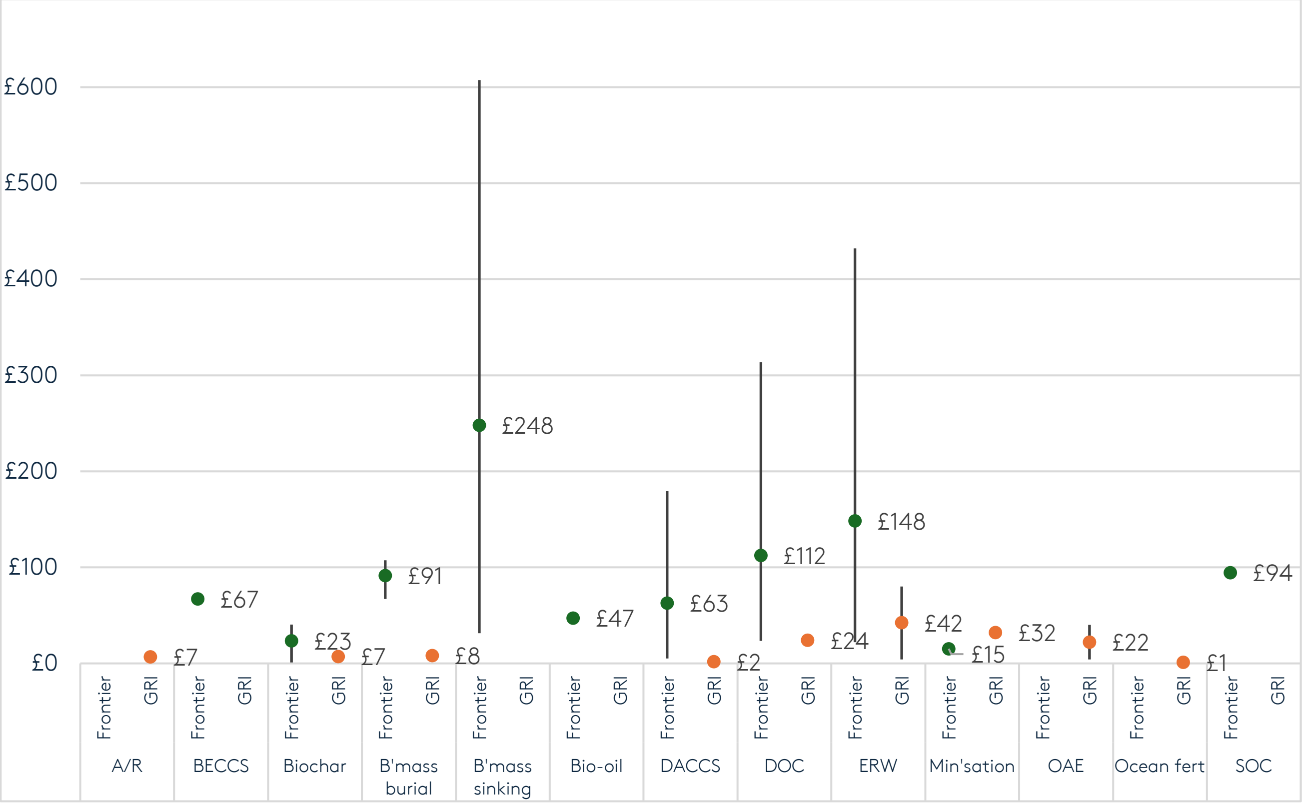
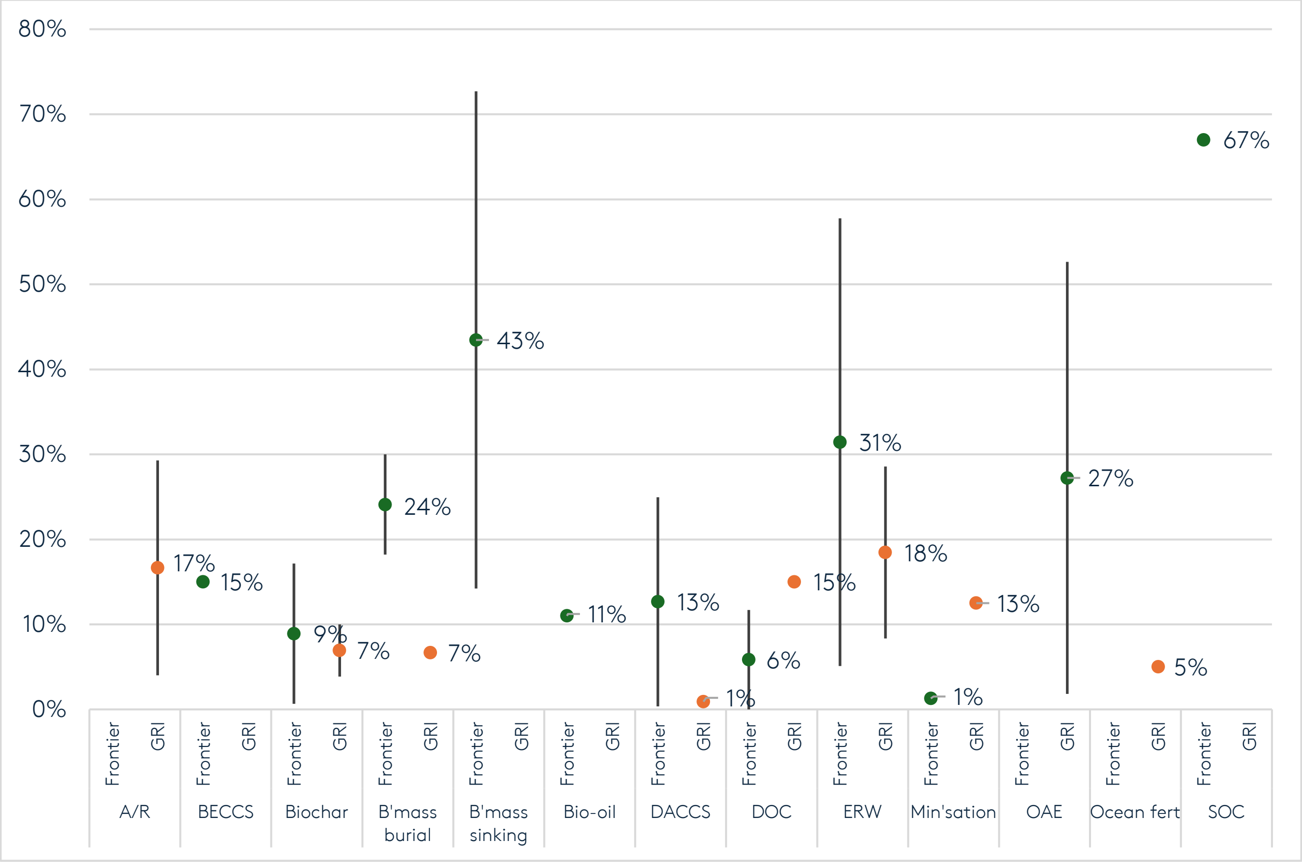


Figure 3.2b. Relative cost of MRV (cost as a % of total cost)



Notes/sources: two datasets are used and are presented in 2024 prices. Orange dots denote data collected from the Grantham Research Institute (GRI) survey. Green dots denote data from Frontier.

How have costs evolved between 2022 and 2024?

Figures 3.2a and b were disaggregated to examine how the absolute and relative costs of MRV have changed over the period 2022–2024. This is an important first step in understanding whether costs are increasing or decreasing as new companies and technologies emerge. Charts illustrating this disaggregation for each method across the Frontier dataset for 2022, 2023 and 2024 and for the Grantham Research Institute dataset for 2024 are provided in the appendix. The analysis shows that average absolute MRV costs across both datasets from 2022–2024 have declined for biochar, biomass burial and DACCS. For DOC the Frontier data shows a steep decline from £314/t in 2022 to £23/t in 2023 (no range – only singular data points) and in the Grantham data there is a minor increase to £24/t (2024) – however, this is a substantial decline from 2022. ERW shows a reduction from £81 in 2022 (Frontier data) to £42 in 2024 (Grantham data); however, Frontier data for 2023 show an average cost of £163 and in 2024, £205. Mineralisation saw an increase from £16 (Frontier data) in 2022 to £32 (Grantham data) in 2024 and marine biomass sinking saw a significant increase in absolute MRV costs from £158 in 2022 to £607 in 2023 (both Frontier data).

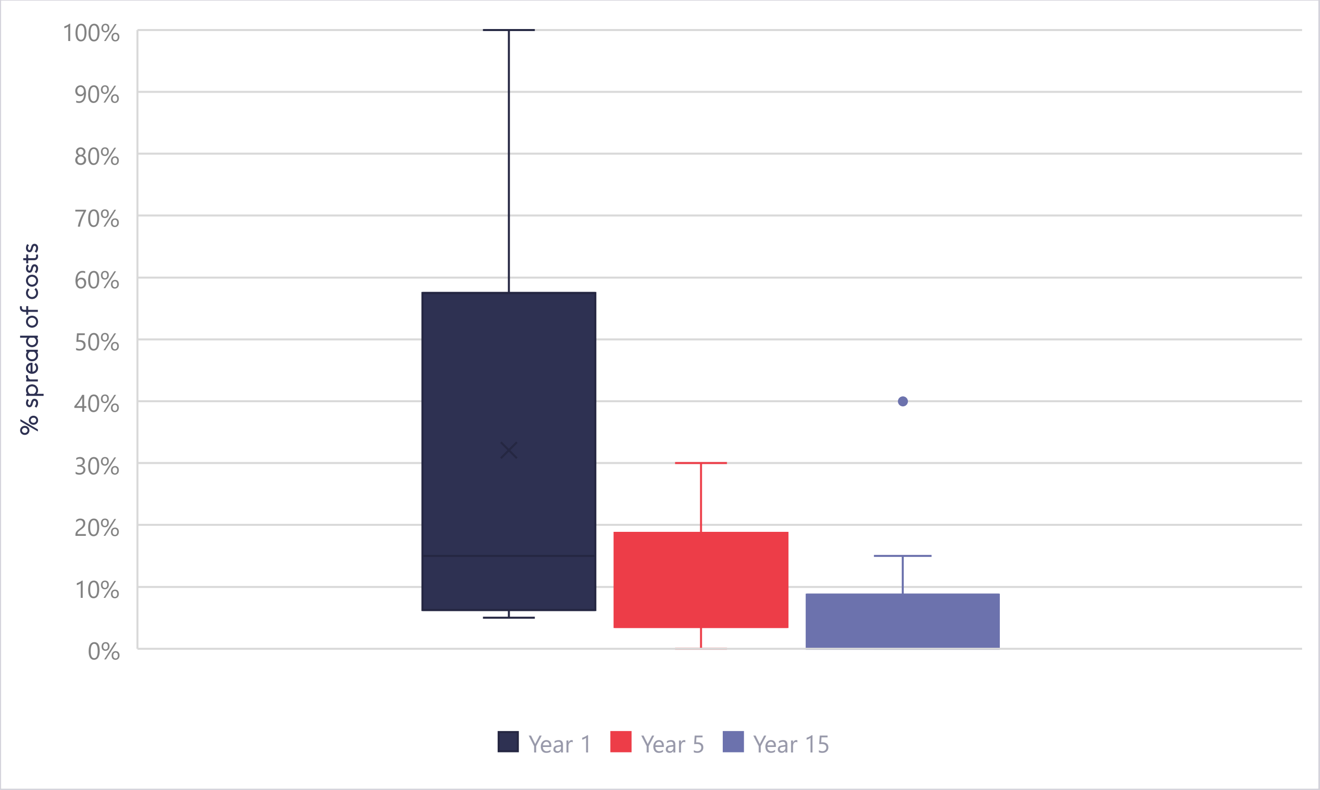
Regarding relative costs, the only methods for which there were clear relative cost reductions between 2022 and 2024 were biochar – falling from a 9% average in 2022 (Frontier data) to 7% in 2024 (Grantham data); biomass burial – from a 24% average in 2022 (Frontier data) to 7% in 2024 (Grantham data); and DACCS – from a 10% average in 2022 to 4% in 2023 and 1% in 2024 (all Frontier data) and also to 1% in 2024 in the Grantham data. Interestingly, ERW saw 11% relative costs in 2022 (Frontier data), which have increased to 29% in 2024 (Grantham data) while DOC saw 12% relative costs in 2022 and 15% in 2024. Both of these methods saw sustained reductions in absolute costs but increases in relative costs, which suggests that the fall in MRV costs has been less steep than the fall in total CDR costs. In contrast, for DACCS and biomass burial, absolute and relative MRV costs have fallen over the last two years. Due to limited data for other methods, it is not possible to discern other noticeable trends.

Spread of MRV costs

Figure 3.3 illustrates how the cost of MRV for CDR is distributed over the first, fifth and 15th years of operation. Respondents were asked: *'What percentages of the total cost per tonne that is attributable to MRV fall in years 1, 5 and 15 of operation?'* Because only two projects had been operating for five years or more, the other respondents forecast their expected MRV costs for Years 5 and 15.

Mean MRV costs as a percentage of total business costs are 30% in Year 1 – a period dominated by high capital expenditure required to establish a CDR project and MRV process, which can include pilot testing of in-situ and field tests of CDR processes and MRV systems. These upfront costs will likely include the purchase and installation of sensors and other necessary equipment, software, and laboratory space/infrastructure. Over time, these initial investments are amortised, leading to a significant reduction in annual costs. By Year 5, mean MRV costs are forecast at 11%. This reduction potentially represents a transition from MRV costs almost wholly comprising CAPEX, to an MRV system reliant on OPEX – such as labour and routine maintenance, rather than large capital outlays. By Year 15, the distribution of MRV costs relative to wider business costs is forecast to be slightly under 8%, with ongoing labour and operational expenses constituting the majority of MRV costs, reflecting the sustained need for periodic data collection, analysis and reporting to ensure the continued effectiveness and compliance of the carbon removal projects. While these costs are projections, it is interesting to note that MRV is expected to constitute baseline costs of around 10% (based on where MRV costs lay in Years 5 and 15) for mature CDR companies.

Figure 3.3. Percentage spread of MRV costs in Years 1, 5 and 15 based on data from the Grantham Research Institute

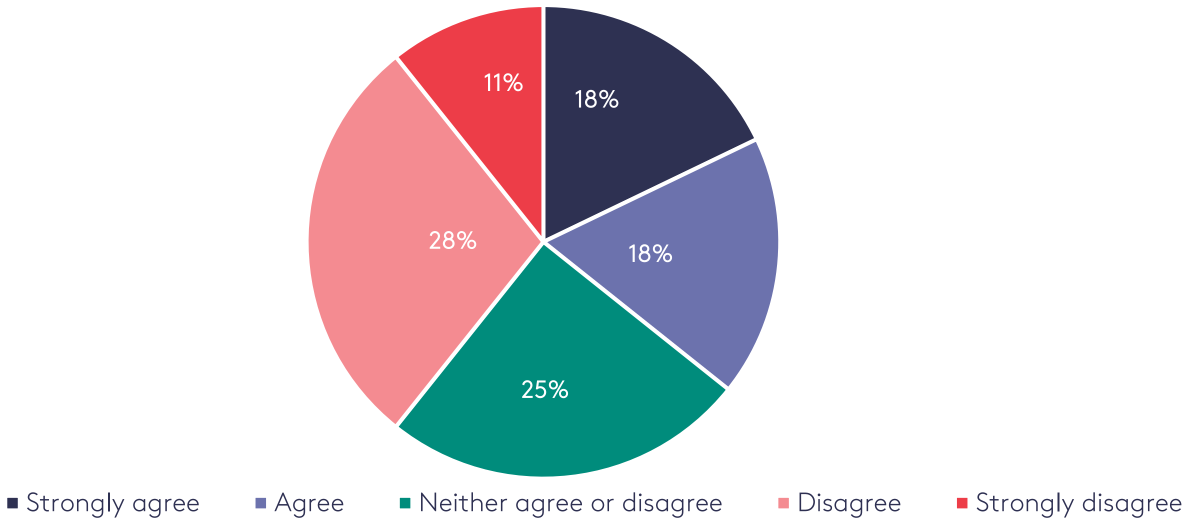


Cost of MRV as a barrier to growth

Survey participants were asked to state the extent to which they agreed with the following statement: *'At present, the cost of MRV is a significant barrier to scaling my company.'*

The aggregate results are presented in Figure 3.4: 28% of respondents disagreed with the statement and 11% strongly disagreed. In total, a greater proportion of respondents disagreed with the statement than agreed, although a higher proportion of respondents strongly agreed (18%) than strongly disagreed.

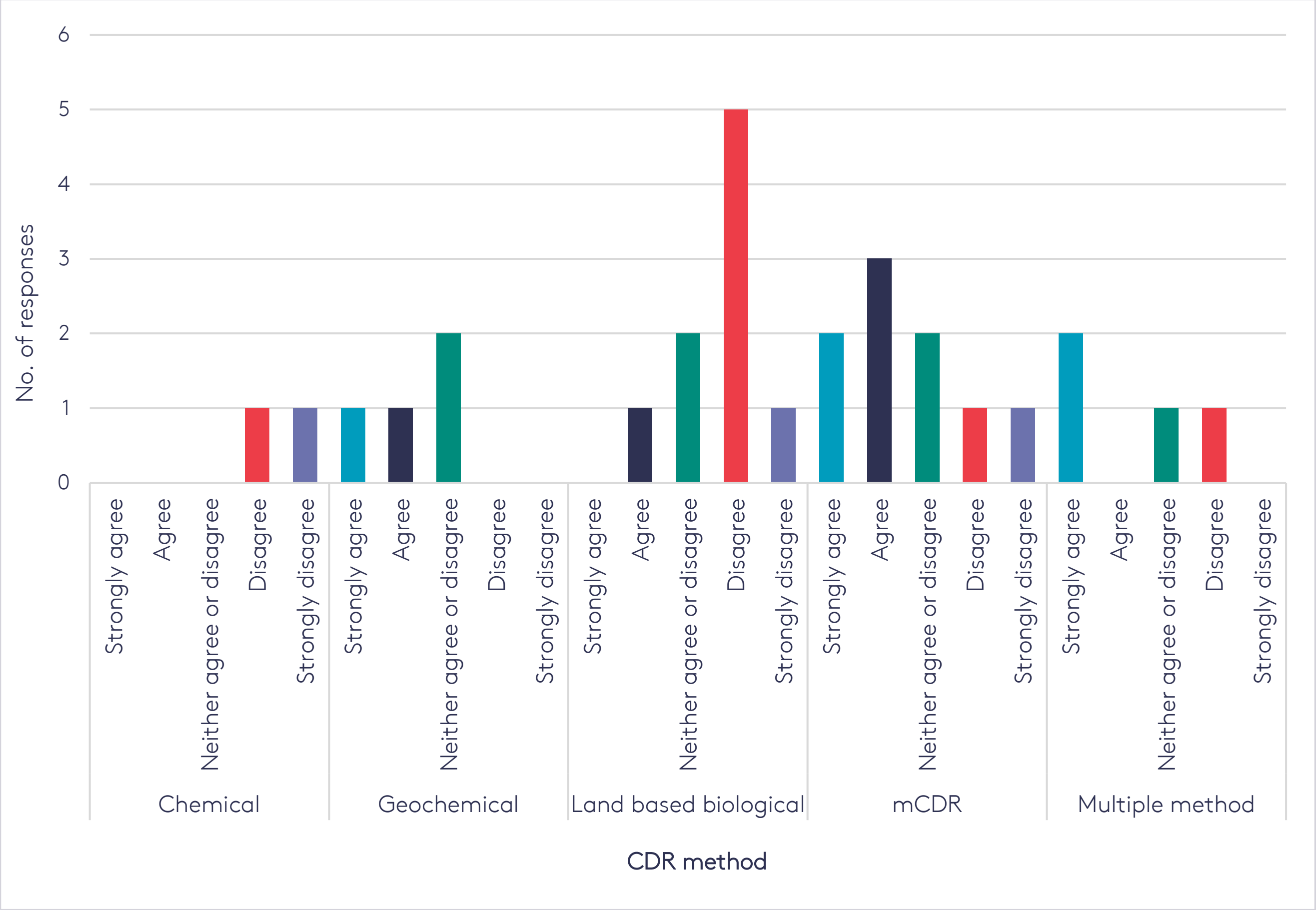
Figure 3.4. Proportion of respondents agreeing or disagreeing that the costs of MRV pose a significant barrier to scaling up their CDR company



Note: The number of respondents was 28.

The extent to which MRV cost is perceived as a barrier differs across methods. Figure 3.5 illustrates that companies using geochemical (e.g. ERW) and marine carbon dioxide removal (mCDR) methods tend to view the cost of MRV as a bigger barrier to upscaling than do companies working with the land-based biological CDR and chemical CDR (e.g. DACCS), with their respondents disagreeing or strongly disagreeing with the statement. For land-based biological methods, predominantly biochar, the majority of respondents disagreed with the statement.

Figure 3.5. Number of respondents agreeing or disagreeing that the costs of MRV pose a significant barrier to scaling up their CDR company, by CDR method



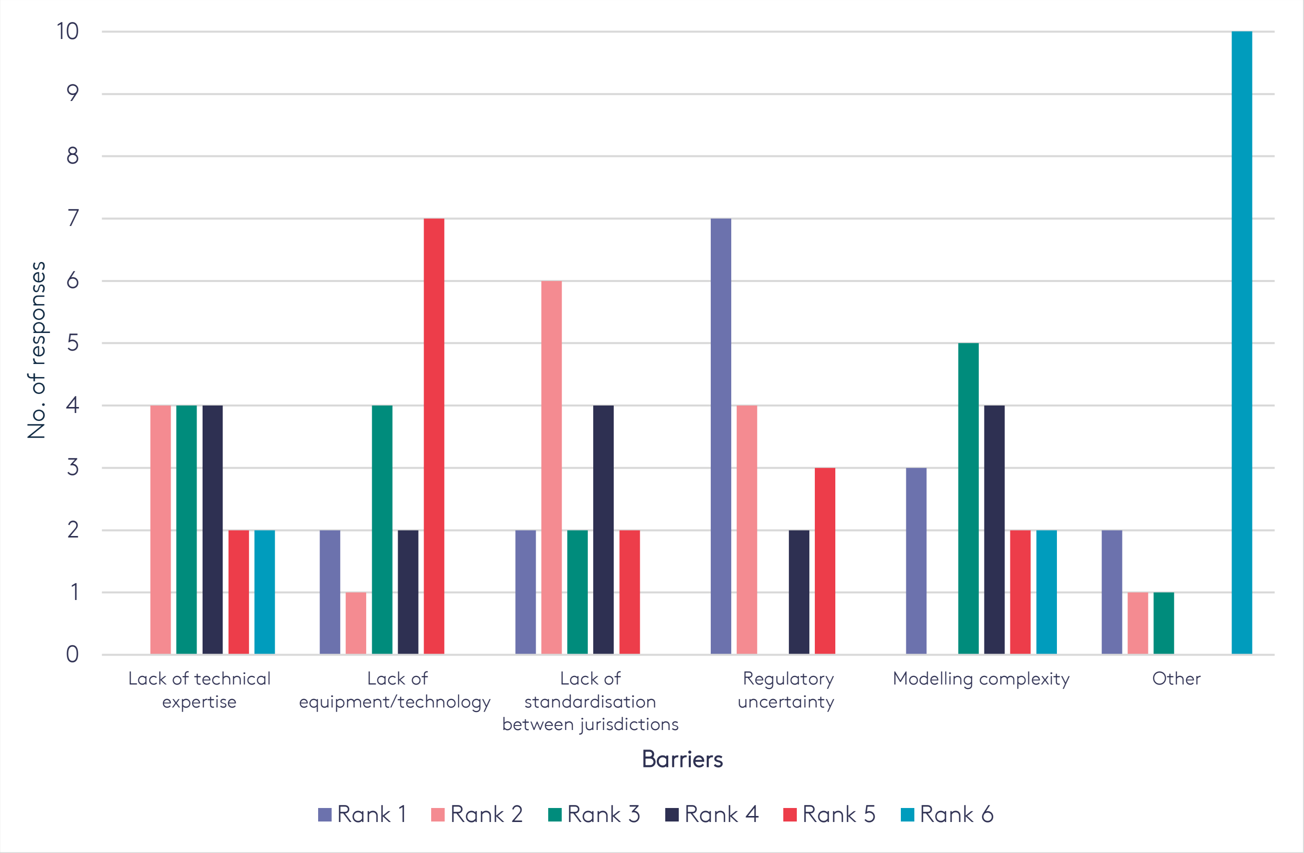
Note: Analysis based on Grantham dataset, broken down by method. The number of respondents was 28.

Ranking of barriers

Although not every method perceives the cost of MRV as a big barrier to scaling, it is still important to understand what the biggest barriers to reducing MRV cost are. Figure 3.6 illustrates the aggregate results. The height of the bars illustrates the number of times each barrier was ranked.

Across all methods, 'regulatory uncertainty' was ranked as the number 1 barrier to reducing costs the greatest number of times. This was followed by 'modelling complexity', which received the second greatest number of rank-1 votes. A 'lack of standardisation between jurisdictions' had the greatest number of rank-2 votes. However, once CDR pathways become established, the desire for greater standardisation and regulatory certainty may become an impediment to innovation. Although this is not yet an issue, it is something that policymakers should be cognisant of. None of the surveyed participants ranked 'a lack of technical expertise' as the biggest barrier and 'a lack of equipment/technology' was ranked as the smallest barrier the greatest number of times.

Figure 3.6. Biggest barriers to reducing MRV cost, as ranked by respondents

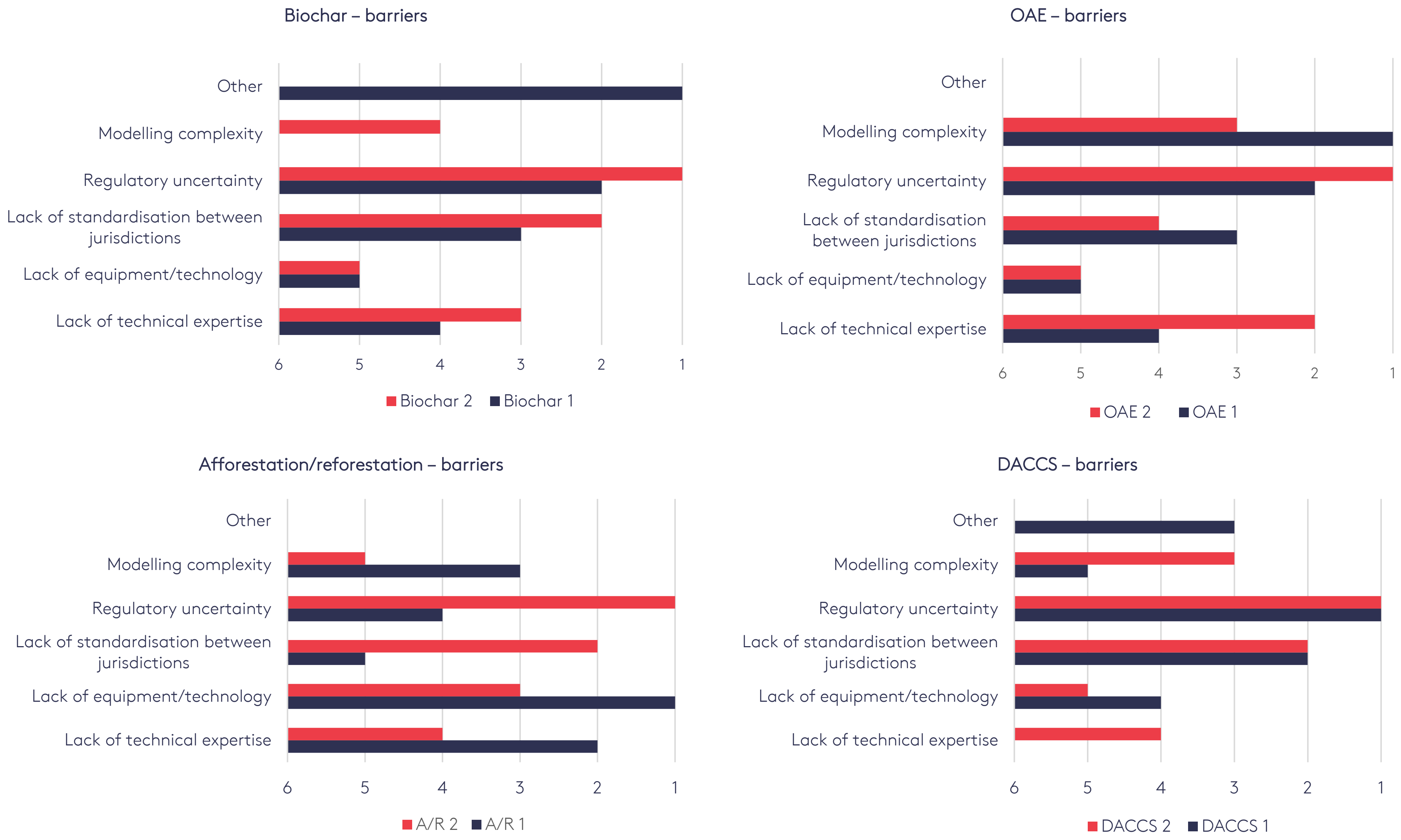


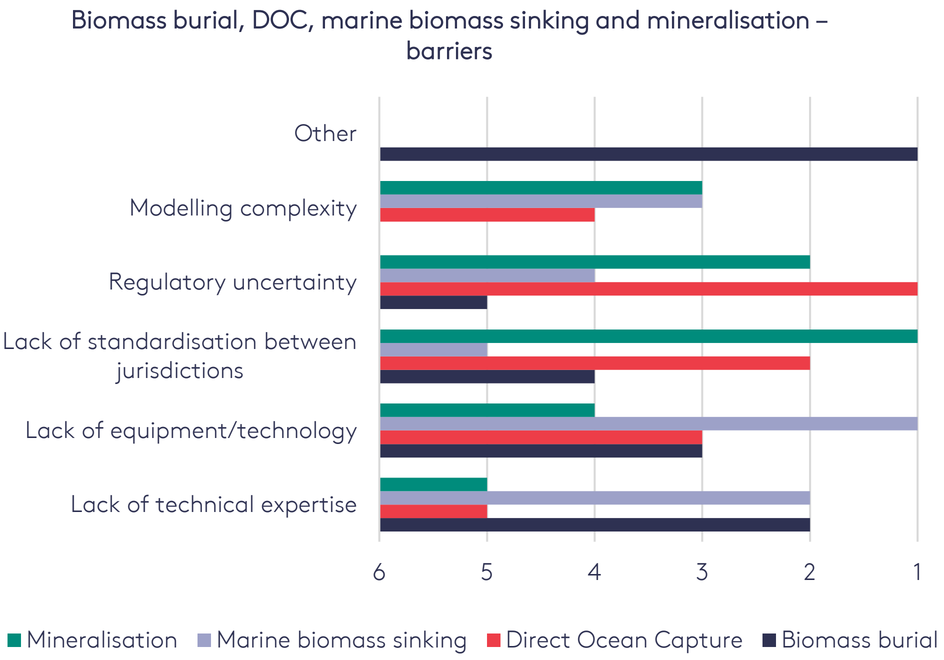
Note: The number of respondents was 28.

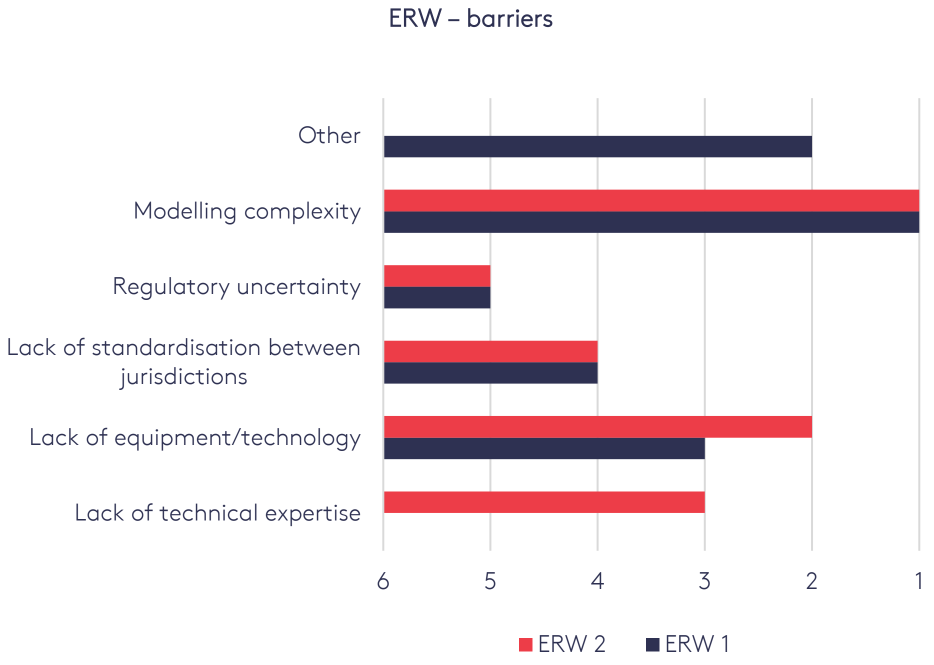
Some barriers may be specific to certain methods. This is further explored below in Figure 3.7. For DACCS, the biggest barriers to reduced MRV cost are regulatory uncertainty and lack of standardisation, with lack of equipment technology and modelling complexity not considered to be significant barriers.

Similarly, for biochar, regulatory uncertainty and a lack of standardisation are considered the largest barriers, and a lack of technology and equipment the smallest barrier. The picture is more mixed for OAE. Although regulatory uncertainty is again a big barrier, a lack of technical expertise and modelling complexity are also barriers to reducing MRV cost. For ERW, modelling complexity is clearly perceived to be the biggest barrier and in contrast to other methods regulatory uncertainty is considered a smaller barrier. For A/R the picture is again quite mixed, with lack of equipment and regulatory uncertainty ranked as the biggest barriers, with a lack of standardisation and lack of technical expertise also considered to be big barriers.

Figure 3.7. Barriers to reducing MRV cost by CDR method, as ranked by two respondents per method (from 1, biggest to 6, smallest)




Biomass burial, DOC, marine biomass sinking and mineralisation – barriers
Other
Modelling complexity
Regulatory uncertainty
Lack of standardisation between jurisdictions
Lack of equipment/technology
Lack of technical expertise
6
5
4
3
2
1
Mineralisation
Marine biomass sinking
Direct Ocean Capture
Biomass burial


ERW – barriers
Other
Modelling complexity
Regulatory uncertainty
Lack of standardisation between jurisdictions
Lack of equipment/technology
Lack of technical expertise
6
5
4
3
2
1
ERW 2
ERW 1

Self-reported MRV certainty thresholds

Lastly, the survey respondents were asked to state the certainty threshold (as a probability that a reported tonne of carbon will be removed at issuance) they are aiming for in their MRV process. The average certainty threshold by method is presented in Table 3.3.

This was then compared with discount factors found in the Frontier dataset. Data taken from the Frontier dataset relies on companies self-reporting uncertainties associated with their CDR process, and a conservative estimation of CO_2 losses within their value chain. It is important to note that these are estimates and given the low TRL of many companies within the sample, the uncertainties will potentially change over time and the thresholds may not be realistic.

Table 3.3. Average certainty threshold across CDR methods

Method	Average certainty threshold in the Grantham dataset (%)	Average certainty threshold in the Frontier dataset (%)
DACCS	99.5	92.2
A/R	95	n/a
DOC	95	90
Biochar	94.5	91.6
Biomass burial	90	80
OAE	90	n/a
Ocean fertilisation	81	n/a
Mineralisation	80	90
Marine biomass sinking	71.5	59
ERW	70.5	78

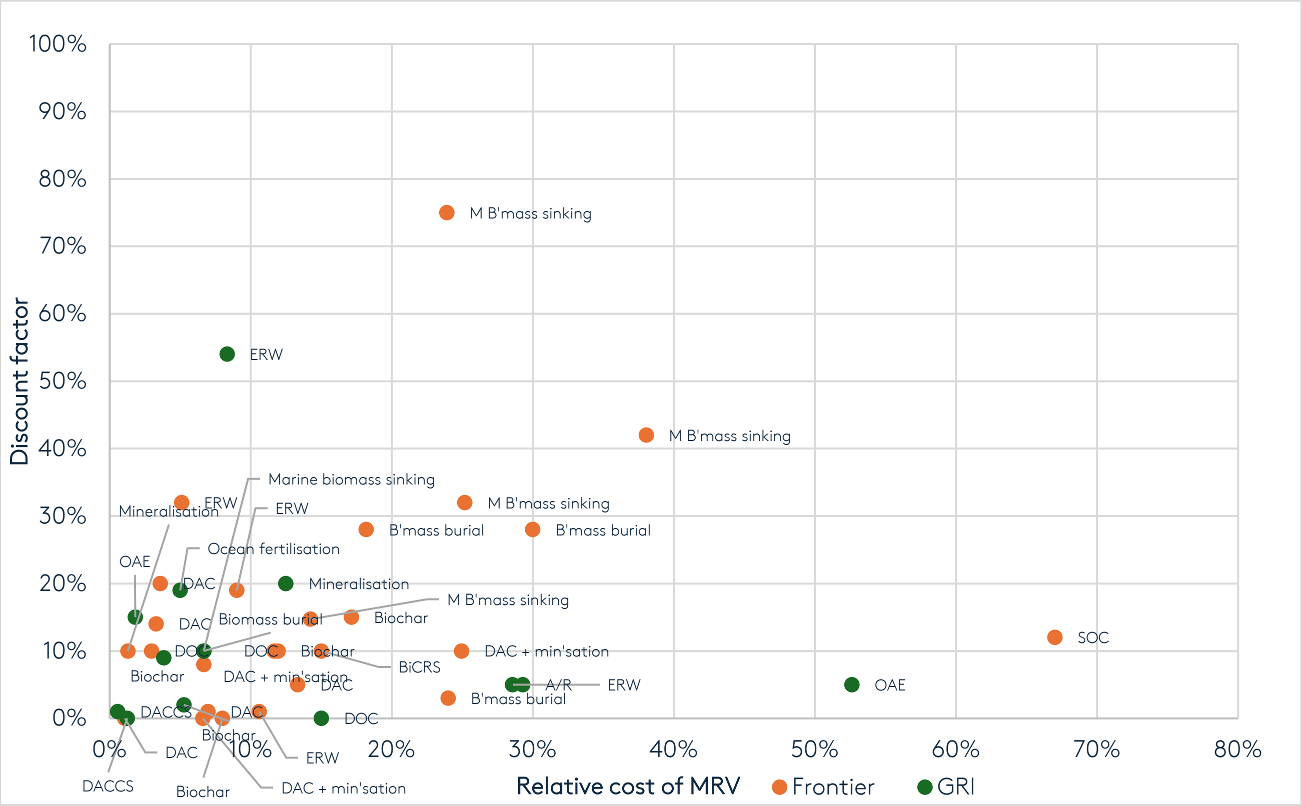
Table 3.3 shows that the DACCS companies self-reported the highest average certainty threshold. Given the relative maturity of geological sequestration used for CCS (and associated protocols that underpin DACCS) and the fact that DACCS is carried out in a highly contained environment, it can be expected that higher certainty is attainable. Thus, MRV is comparatively less complex for this method as removed and stored CO_2 can be readily metered as it is being injected into the subsurface and the movement of the injected CO_2 can be reliably tracked as it moves through the geological storage site (Mac Dowell et al., 2022).

In contrast, ERW companies self-reported the lowest average certainty threshold in the Grantham dataset and marine biomass sinking companies self-reported the lowest average certainty threshold in the Frontier dataset. For these companies, this could reflect that calculating net removal is inherently more complex where system boundaries are difficult to define and monitor, as supported by Figure 3.7 which shows that modelling complexity was cited as the biggest barrier to reducing MRV costs for ERW. For example, the mineral substrate might be distributed over a large area, with the carbonation reaction a function of numerous factors that need to be assessed temporally and spatially in addition to ambient temperature, predominant substrate and land use, presence of water and soil pH (ibid.). For marine biomass sinking, the low certainty threshold could reflect a lack of equipment and technology to accurately quantify net removals (as highlighted in Figure 3.7), which may also be a driver of higher MRV cost (see Figure 3.3). Surprisingly, a respondent from an OAE company reported a 90% certainty threshold, given the well-known challenges in attributing net removals to human intervention at present.

Figure 3.8 shows the relationship between MRV cost and the self-reported discount factor in the Frontier dataset and the certainty threshold requested in the Grantham survey. These two variables are not completely aligned, but, in effect, both variables present the same information: i.e. how much a CDR supplier should discount their removed tonnes due to uncertainties across the value chain or within the MRV process itself.

Analysis of the discount factors used in both the Grantham and Frontier datasets did not yield any conclusive results. Our hypothesis was that for companies that self-lower discount factors (i.e. to less than 10%), this would be reflected in higher MRV costs. Sixty per cent (24) of the CDR companies reported discount factors of 10% or less. Figure 3.8 indicates a mild causal relationship between the size of the discount factor and the cost of the MRV process. This is most apparent for the Frontier dataset. Similarly, when comparing TRL and MRV cost/tonne, few clear relationships are apparent across each dataset.

Figure 3.8. Relationship between the relative cost of MRV and the discount factor used in the Grantham Research Institute and Frontier datasets



Qualitative results

Protocols

The survey asked for detailed qualitative information for a series of questions, which were answered by 29 respondents. The survey requested whether the companies used an external protocol that had been developed by a standards development organisation such as Verra or Puro to monitor, report and verify the performance of their CDR process. Their responses are shown in Table 3.4. Seven respondents stated an outright 'no', which were for marine biomass sinking, biomass burial, DOC, ocean fertilisation, A/R and mineralisation. Five selected 'other' and in their text-based response said 'not yet'. These were for ERW, mineralisation, BECCS, DACCS and OAE. Four provided further information on which standards organisation they would be working with in the future, which was either Puro or Isometric. One respondent stated, 'We will use Puro.earth's DAC+S and BEC+S methodologies, the CCS+ Initiative's work when it's complete, and we can also comply with the Climeworks + Carbfix methodology' (BECCS/DACCS/mineralisation respondent).

Fourteen respondents said 'yes' to using protocols (several in some cases), which included those from Isometric (OAE – two respondents; DACCS – one respondent), Puro (biochar – three; biomass burial – one), Verra (BECCS, ERW, biochar, soil carbon in croplands and grasslands, A/R, biomass burial – one; mineralisation – one), CSI (biochar – two), and one each for social carbon (no specific protocol specified), Article 6 bilaterals (BECCS, ERW, biochar, soil carbon in croplands and grasslands, A/R, biomass burial), WBC (biochar), Gold Standard (BECCS plus mineralisation), EBC Sink (biochar) and Carbonfuture (biochar). One respondent (OAE) stated they have developed an internal protocol verified by a third party. The responses were from multiple countries and the companies varied in their TRL between levels 5 and 9, with six companies being at TRL 9, of which two had removed more than 5,001 tonnes of CO_2.

Out of the 29 respondents (see Table 3.4), 18 stated that they had developed their own MRV protocol to assess the performance of their CDR process (with MRV protocol defined as 'a multi-step process document to guide the measuring/monitoring of a CDR activity including how data is compiled and reported on and the correct process for third party verification of results'). More than half (10) of these companies were located in North America, and covered all CDR processes apart from DACCS and ocean fertilisation, and half of the processes were small-scale projects removing 0–50t of CO_2. Four selected 'other', of which one was in the process of developing a protocol, one said they were not doing so yet but will this year, one stated 'first party only so far, third-party validation in progress', one did not complete this part of the survey; and seven said 'no', they had not developed their own protocol. This 'no' applied to BECCS, mineralisation, biochar and DACCS companies mostly located within Europe with low to medium TRL, and 0–50 tonnes of removals to date.

For those respondents who said they had developed their own MRV protocol, they were asked to explain why, expand upon the process of development, and describe any commonalities with existing MRV standards. A key theme that was seen in the 18 responses was that they considered it necessary to develop a protocol because nothing suitable already existed, e.g.: 'No MRV process exists for this technology yet, and we are experts in this area' (DOC respondent). Linked to this was the idea that CDR is unique and novel, meaning that internal protocols and technology have to be created: 'Until about a year ago there was no MRV protocol for ERW. So we had to develop our own. However, now that Puro and Isometric are actively involved, this changes and we are moving away from our own protocol' (ERW/mineralisation respondent). Seven respondents stated that it was important that any protocol adhered to standards/external review/working with others, making comments such as 'Data scientists verify the data' (A/R respondent), and 'We use the standards (Puro and CSI) to define what data we need to report' (biochar respondent).

Respondents viewed transparency as being very important, referring to publishing information on their websites and buyers having asked them to explain what they produce by way of project design documents (PDD): 'PDD and monitoring reports have been requested by buyers' (biochar respondent).

Other interesting individual specific comments regarding MRV standards included:

- 'The direct ocean capture process is unique and hence a lower priority for the commercial MRV protocol developers.' (DOC respondent)
- 'There is a standard default percentage that is applied to all credits that we are not able to count.' (Mineralisation respondent)
- 'The word MRV is misleading, as it is often just used for monitoring through an additional provider in the biochar space. The MRV is split up in biochar, and there is not one provider who is actually doing everything.' (Biochar respondent)
- 'Only if we need/want to hide certain information in the supply chain we use a tracking provider as a Chinese Wall between the different parties active in the CDR process of application of biochar. Tracking providers often call themselves MRV, which is simply wrong in the biochar world and should be clarified very soon.' (Biochar respondent)

Table 3.4. Overview of MRV protocol use by respondent companies, mapped against type of CDR process, technological readiness level (TRL) and CO_2 removal to date

CDR process[es] engaged in, per company	TRL	Years CDR project has been operational	Tonnes of CDR removed to date	Currently using external protocol developed by a standards development organisation?	Has developed own MRV protocol?
A/R	9	5+	>5,001	No	Other
A/R	9	1–2	0–50	Yes – Global Tree C-Sink by Carbon Standards International	Yes
BECCS	8	0–1	0–50	-	Yes
BECCS, DACCS, Mineralisation	7	1–2	0–50	Not yet	Other
BECCS, ERW, Biochar, Soil carbon in croplands and grasslands, A/R, Biomass burial	9	3–4	>5,001	Yes – Verra, Social Carbon, Article 6 bilaterals	Yes
BECCS, Mineralisation	9	2–3	1,001–2,500	Yes – Gold Standard	No
Biochar	7	0–1	0–50	Yes – EBC (European Biochar Certificate)	No
Biochar	9	5+	>5,001	Yes – Puro, EBC Sink	No
Biochar	9	4–5	2,501–5,000	Yes – Puro, CSI	Yes
Biochar	6	1–2	1,001–2,500	Yes – Puro	Yes
Biochar	6	0–1	0–50	Yes – CSI Global c-sink Methodology + Carbonfuture as MRV partner	No
Biomass burial	7	0–1	51–100	Yes – Puro TSB	Yes
DACCS	5	0–1	0–50	Yes – Isometric	No
DACCS	5	0–1	0–50	Not yet	No
DACCS	4	0–1	0–50	-	No
DOC	6	1–2	0–50	No	Yes
DOC	4	2–3	0–50	No	Yes
ERW	9	2–3	2,501–5,000	Not yet	Yes
ERW, Mineralisation	8	5+	>5,001	Not yet	Yes
Marine biomass sinking, Biomass burial	4	0–1	0–50	No	Yes
Mineralisation	7	0–1	0–50	Yes – Verra	Yes
Mineralisation	6	0–1	0–50	No	Yes

CDR process[es] engaged in, per company	TRL	Years CDR project has been operational	Tonnes of CDR removed to date	Currently using external protocol developed by a standards development organisation?	Has developed own MRV protocol?
OAE	7	0–1	0–50	Yes – Isometric – Ocean Alkalinity Enhancement from Coastal Outfalls v1.0	Yes
OAE	6	1–2	51–100	Yes – Isometric	Yes
OAE	5	0–1	0–50	Not yet	Other
OAE	9	1–2	51–100	Yes – Developed internal protocol verified by a third party	Yes
Ocean fertilisation	6	0–1	0–50	No	Other
Other	7	1–2	0–50	No	Yes
Soil carbon in croplands and grasslands	-	-	-	-	Yes

Note: There were 29 respondents. Only 19 respondents included detailed information on MRV costs. A dash indicates no data was provided. For the final column, the question asked was: 'Have you developed your own MRV protocol (multi-step process document to guide the measuring/monitoring of a CDR activity including how data is compiled and reported on and the correct process for third party verification of results) to assess the performance of your CDR process?' Textual answers under 'other' have been summarised in the preceding paragraphs.

MRV costs

The survey asked respondents to outline which operational or capital expenditures, specifically related to MRV, are most costly. Three key themes were apparent in the answers:

- **Operational expenditure**, which was mentioned particularly in relation to fieldwork for A/R and mineralisation, and DACCS in terms of labour costs in a new company.
- **Capital expenditure** such as costs for set-up, measurement instruments and software. One company highlighted the unknowns of capital expenditure: 'We don't know yet. With DAC, the MRV cost will be split between the measurement instruments and associated software for in-house measurement (as part of instrumentation and control systems), and any costs associated with the MRV service provider. I expect that the CAPEX on the sensors is the most costly' (DACCS respondent).
- **Provider and third-party costs**, for example: 'laboratory testing by third parties, and intermittent sub-surface testing provided by third parties' (BECCS, DACCS, mineralisation respondent). One DOC respondent stated, 'The $30 per tonne I quote is the number we have been told by the MRV company our offtake customer prefers. We have no breakdown of their costs.'

Further themes included:

- **Digitising and automating MRV:** this was the main theme discussed by nine respondents when asked to say what the key innovations would be to reduce the future cost of MRV for their CDR process (these respondents were: ERW, mineralisation – one; BECCS, ERW, biochar, soil carbon in croplands and grasslands, A/R, Biomass burial – one; BECCS, DACCS, mineralisation – one; OAE – one; DOC – one; A/R – two; mineralisation – one; biochar – one). For example, one respondent highlighted the importance of automation 'in the internal data verification process' (A/R respondent). This theme also included comments on 'better measuring' (ERW, mineralisation respondent), and the use of remote sensing (A/R respondent; BECCS, ERW, biochar, soil carbon in croplands and grasslands, A/R, biomass burial respondent).

- **Cost reduction for instrumentation**, with five comments on this (from biomass burial; DACCS; OAE; ocean fertilisation; and marine biomass sinking plus biomass burial respondents).
- **Better modelling and accuracy**: for example, 'Digitalisation and automation, as well as being able to use historic data as reference points for new data (e.g. application of ML/AI [machine learning/artificial intelligence] to interpreting datasets)' (BECCS, DACCS, mineralisation respondent).

Other individual responses included 'the biggest innovation is in policy' (DOC respondent), and 'streamlined reporting processes' (OAE respondent).

The survey asked how the uncertainties associated with the current MRV process would be affected by increased investment in parts of the MRV process. An example was given, asking respondents how additional investment to increase sampling density reduces uncertainty in terms of a percentage. Responses ranged from saying it was 'unclear' how this reduces uncertainty (two respondents: ERW, mineralisation; DOC), to pointing to the need for investment in sensors and scanners, and to the need for investment in surveys and sampling (reiterating earlier responses). One respondent said that 'New sensors could reduce uncertainty by 30%-plus' (OAE respondent), while another said that 'Increased surveys could increase certainty to 90%' (A/R respondent). Another stated: 'Investment to increase either accuracy of instruments with wide spatial range or sampling density of instruments with low spatial range would reduce uncertainty by 10%' (mineralisation respondent). Thus, there were large differences in the responses to this question, reflecting the differences in CDR methods.

Respondents were asked if they would be able to explain how the costs of different MRV approaches influenced their choice of measurement and monitoring method. For example, did the quality preferences of buyers influence the MRV process chosen, or was there a specific budget for MRV in mind which then required finding a suitable method with sufficient accuracy? Cost was seen to be important but did not appear to be the overriding factor, with respondents seeing a need to 'balanc[e] overall project budget and accuracy' (mineralisation respondent), with comments such as 'cost only influenced which provider' (DACCS respondent), that it was a 'blend of requirements and budget' (DOC respondent), and that 'the cost implications are not understood, even by them [MRV providers]' (ERW, mineralisation respondent). One respondent stated that 'some project developers want more MRV than is outlined in methodologies' (BECCS, DACCS, mineralisation respondent), which aligned with another respondent who specifically stated that 'quality preferences of buyers' are the driver (ERW, mineralisation respondent). The design and quality of standards and protocols design was another clear theme, with some respondents saying that this is what defines the costs. One respondent noted that 'no approaches other than conventional mensuration were available' (A/R respondent).

When asked specifically about the balance of any trade-offs between accuracy of measurement and the cost of the wider MRV process, there were a wide range of answers, which tended to include the importance of balancing accuracy, meeting set standards and commercial needs, and not being driven by costs alone: e.g. 'We are currently meeting the requirements set by standards/methodologies. When asked to do more, we charge more, so the balance is defined commercially' (BECCS, DACCS, mineralisation respondent); 'We went for high quantity MRV over restricting cost too far, as [it is] important to start from something that proves you can do it, then can bring costs down' (DOC respondent). Six of the 12 respondents to this question (DACCS; DOC; ERW plus mineralisation; OAE; biochar; A/R) specifically mentioned 'maximising accuracy'. It was clear that some respondents were concerned about the future: e.g. 'The problem has not emerged yet, we foresee such trade-offs when various protocols entail different requirements and imply different certification levels' (OAE respondent).

4. Discussion and recommendations

In this section we first ask how pervasive a barrier to scaling up CDR the cost of MRV is, before setting out the implications of our research results further, providing recommendations under the following areas:

- The policy challenge of reducing cost barriers to MRV
- Innovations to reduce costs
- Getting comfortable with uncertainty
- Approaches to MRV
- Informing assumptions for equivalence ratios

Some of our recommendations are targeted specifically at the UK government because this policy report was co-created with officials from the UK's Department of Energy Security and Net Zero (DESNZ), where MRV for CDR is a topic of active policy development.

Is the cost of MRV a pervasive barrier to scaling up CDR?

The hypothesis of this research was that MRV would be considered a significant barrier to scaling up CDR. This proved true for some methods, but not consistently across the survey sample. Survey responses indicate mixed perceptions of MRV costs as a barrier to upscaling. While 28% of respondents disagreed and 11% strongly disagreed that MRV costs are a significant barrier, only 18% strongly agreed. Unsurprisingly, companies that disagreed or strongly disagreed have lower average MRV costs – of 6.6% – compared with 25.9% average costs for companies that agreed or strongly agreed with the statement. There was no obvious trend related to location, age of the company or scale of the CDR method across the answers.

The implication of this result is that policies to reduce MRV costs need to be part of a broader policy package that addresses innovation challenges within the CDR value chain, e.g. in developing more effective sorbents or amines,[2] more efficient pyrolysis techniques and core R&D. Developing technological breakthroughs, scaling up production and harnessing efficiencies through learning by doing will likely do more to lower average CDR costs than targeting MRV solely. This is encouraging in that MRV may not be the most costly barrier to upscaling as once thought, but high costs still pervade the CDR system. However, there may be differences between methods of CDR. Average relative costs for marine biomass sinking were 43% (in the Frontier dataset), 27% for OAE (Grantham) and 31% for ERW (Frontier), which were high compared with biochar (9% – Frontier, 7% – Grantham) and mineralisation (1% – Frontier, 13% – Grantham). Policymakers will need to discriminate between those CDR methods that have high and low MRV costs and consider whether methods with consistently high MRV costs are being inhibited and thus worthy of deployment support or subsidies.

In general, the cost of MRV for marine CDR was smaller than first anticipated, even though those companies perceived the cost to be a big barrier to upscaling. Higher costs could be expected for two reasons. Firstly, the oceans are a highly dynamic and variable environment and the physical and biogeochemical processes relevant to mCDR quantification are complex. Consequently, the ocean biogeochemical models that run simulations are very computationally expensive (Yankovsky et al., 2024). Secondly, interventions that are perceived as 'tampering with nature' or characterised as unnatural are more likely to be rejected (Nawaz et al., 2023). For example, Planetary's 2023 trial in Cornwall resulted in widespread opposition and protests (Weeks, 2023). These socio-environmental and ethical concerns are likely to increase the cost of CDR methods that are not perceived to have a social licence to operate.

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[2] Sorbents are materials, either solid or liquid, that capture and retain CO_2 from the air or flue gases, commonly used in DACCS and other CCS applications. Amines are nitrogen-containing sorbents and absorb CO_2 through amine scrubbing – where the amine reacts with CO_2 to form a compound that can later be separated and stored or reused.

In response to this and to mitigate potential opposition it could be expected that mCDR companies adopt higher standards, either at the behest of regulators or of their own volition. All else being equal, greater regulatory stringency or shifting norms regarding what constitutes 'best practice' would imply higher MRV costs.

Treating barriers to reducing MRV costs as a policy challenge

The barriers to reducing MRV costs have coalesced around a need for regulatory certainty and a lack of standardisation between jurisdictions. This is a policy barrier and is present across all methods, according to our research. This barrier is surmountable given that jurisdictions such as the EU and UK are developing jurisdictional CDR methodologies and standards which will provide policy certainty in the short to medium term. This finding aligns with results from Yang et al. (2024), who assess policy support options for BECCS and DACCS deployment in Europe. Their paper highlights that CDR actors (drawn from industry, academia and NGOs) across both BECCS and DACCS see a lack of long-term policy certainty as one of the critical barriers to scaling up the industry alongside government support to set clear accounting and MRV standards.

Not all jurisdictions are moving in parallel. The US has not yet elected to develop national quality standards, with MRV developments being largely driven by the standard-developing organisations and CDR project developers. The UK Government has also concluded that few existing MRV methodologies are suitable to endorse in their current form; its intention is now to establish and define its own MRV methodology. This will be delivered by the British Standards Institution, which recently won a tender to develop Minimum Quality Thresholds for DACCS and BECCS.[3] While this is potentially a positive step forward in terms of creating policy certainty and robust governance, it could add further complexity to an already complex regulatory environment.

These issues present challenges and opportunities for policymakers looking to drive down MRV costs. Misalignment between large jurisdictions on standards could pose a problem for the nascent CDR industry, which could worsen over time as jurisdictions develop their own bespoke policies. At present it is difficult to make comparisons of MRV cost because it is influenced by the demarcation of system boundaries, which differs within and across methods and jurisdictions.

For some methods, such as DACCS, this is perhaps less of an issue because removed carbon is transported and stored in a collective reservoir owned by a transport and system operator. For methods that utilise biomass feedstocks, indirect costs – such as efforts to find compliant feedstock sources – may or may not have been captured in the data, depending on where the system boundaries were drawn and where the costs are accounted. As discussed above as being a limitation, not knowing exactly where the system boundary has been drawn for each data point makes it challenging to know if the compared projects are similar or dissimilar in scope.

Attempting to converge on universal quality criteria will present particular challenges for removal methods with complex value chains, as to do so requires harmonisation across several steps. For example, BECCS has a long value chain (including biomass sourcing, energy conversion, carbon capture and carbon storage) relative to other methods, requiring convergence on several contested areas such as feedstock sourcing and land use change. This differs from DACCS which has a comparatively simpler value chain, with the main issue relating to secondary effects in local energy networks. Any centralised effort to develop quality indices for CDR therefore must be attuned to the different characteristics of CDR methods. Quality indices could also recognise that CDR can have different use cases (e.g. compensatory claims versus catalytic buyers), for which the same level of quality is not always required. Expectations for MRV may need to be dampened and policy frames adapted accordingly.

Collaboration and alignment between the EU, the UK and the US represents a substantial opportunity to align quality standards for which the majority of novel and conventional removal

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[3] See https://bidstats.uk/tenders/2024/W40/831914486.

activity is occurring and where demand is greatest. Ensuring buyers can easily make direct comparisons between projects assessed by the same protocol in different jurisdictions represents a significant opportunity to reduce costs, as projects can then align processes with a singular MRV protocol. Evidence from our key informant discussions highlighted that there are few standardised approaches to collecting data across the variety of different CDR methods. Inconsistent completion, compilation and reporting of samples, measurements and monitoring of various elements of the CDR process renders it challenging to accurately compare the relative strengths of an MRV approach and make a fulsome assessment of the performance of a CDR method. Ensuring that MRV data is collected in a standardised format, is transparent and hosted on financially unconflicted registries represents a substantial opportunity to support the upscaling of CDR.

It is important to recognise that for some methods, MRV is underpinned by large model-based datasets. For example, oceanographic models will need to be used because of the vast temporal and spatial scales of the ocean. This is not necessarily an inherent reflection of the uncertainty of a process, but rather a practical reflection of the scale on which mCDR is operating. Inevitably, this produces huge quantities of information, which can make it practically challenging for a company to make such a dataset transparent even if the will is there. To make simulations auditable, with standardised outputs, it is necessary to provide support for hosting and storing information. Transparency is important within the market to ensure proper oversight and scrutiny and also to ensure innovation and best practice can diffuse. However, this desire runs into a number of challenges. Firstly, early stage companies or those CDR companies using nascent methods may not even have accurate data on many aspects of their MRV process. Secondly, there is little reason for companies to willingly pass over proprietary, commercially-sensitive information. Where this need for transparency may be more readily fulfilled is in instances where CDR companies are in receipt of public funds and they are then compelled to divulge MRV cost information to regulators. Regulators could then aggregate, anonymise and host relevant information.

Recommendation 1: In the UK, the Department for Energy Security and Net Zero (DESNZ) should prioritise harmonising MRV practices and principles with jurisdictions such as the EU and US and focus on developing common MRV data collection and management practices in order to better facilitate interoperability and cross-jurisdictional comparisons. At the same time, the desire to standardise must not stifle innovation in MRV protocols. Protocols must be adaptable and flexible without enshrining standards that become outdated in a few years' time. This could be practically achieved by committing to semi-frequent review and consultation periods and by establishing working groups to build consensus views from across the industry to ensure best available practice is reflected in MRV policy.

Recommendation 2: Instilling greater transparency is a way to overcome information asymmetries that stymy market development and increase costs. Such transparency could be a precondition for receiving public funds. Additional support for expensive data-sharing infrastructure is needed in order to make large datasets and simulations publicly available and auditable.

Key innovations to reduce MRV cost

Our qualitative results provide more indication of what factors might reduce costs. The primary factor that emerged was digitising and automating MRV. Respondents from various sectors highlighted the significance of automation, particularly in data verification and remote sensing for better measurement. Additionally, respondents raised a need for improved modelling and accuracy and investments in sensors and other monitoring innovations to drive down costs.

The results therefore indicate that investments to reduce the cost of MRV are best made in automating and digitising processes of monitoring and reporting – across all CDR methods. It is critical that a standardised reporting framework and digital architecture is developed that can be utilised by registries, standard-developing organisations, regulators, validation and verification bodies and the projects themselves. Standardising MRV data collection and storage across all CDR projects (or at least where practical) can do much to reduce transaction costs throughout the supply chain, enable better analysis of CDR efficacy and help buyers to better discriminate between projects using the same protocol.

From the nine respondents that answered questions relating to a breakdown of operational and capital expenditure per tonne of removed CO_2, all respondents bar two said the costs were OPEX-heavy. Looking at specific operational expenditures, labour was the most costly item, with responses ranging from 'fieldwork at sea' (DOC respondent) to 'labour expenditure' (mineralisation respondent) to 'data collection in the field' (A/R respondent). Other respondents highlighted procurement of 'monitoring equipment' (biomass burial respondent) and 'sensors' (DACCS respondent) as the most costly capital expenditures and self-reported these to be higher than OPEX. This result implies a need for policies supportive of upscaling CDR to be reflexive and adaptive in order to cater to the varied characteristics and cost profiles of different CDR methods. This may involve more traditional support for CAPEX i.e. tax credits and direct subsidies to defray high labour costs for other methods. The results do not support a case to provide blanket public support for all CDR companies to mitigate high MRV costs. Instead, as the respondents indicated, support should be targeted to research, demonstration and deployment to resolve outstanding research questions and to provide CAPEX support for laboratory space or sensors to support early-stage companies to proceed from start-up to maturity.

Governmental support programmes can be an important lever in this regard. For example, the US, while not developing a national CDR quality standard, has made targeted investments to improve MRV processes for marine CDR pathways through the SEA-CO2 programme to advance cost-effective MRV alongside a $15 million funding call by the Department of Energy to develop method-agnostic MRV best practices and technologies. Well targeted research projects focusing on solving clearly defined and realistic foundational research questions will be effective at resolving uncertainties. When coupled with targeted research to develop next generation sensors, remote sensing applications, AI and modelling, MRV costs, particularly for mCDR, can be expected to fall.

For the UK, parallels can be drawn from both the Direct Air Capture competition and the Net Zero Hydrogen Fund (HM Government (2024), which were seeded with £100 million and £240 million respectively, to support greenhouse gas removal and low-carbon hydrogen projects that can be deployed on the basis of capital expenditure support. Using this fund as an example, the UK Government could set up a dedicated innovation fund for MRV for CDR, with an explicit remit to support MRV CAPEX for a broader range of methods, including those for which MRV cost is particularly high.

Recommendation 3: To effectively reduce MRV costs in the UK, DESNZ should develop MRV support mechanisms, such as a dedicated CDR innovation fund, that are adaptive and recognise the varying needs of different CDR processes by supporting MRV cost reductions. This could be in the form of, for example, targeted CAPEX support for advanced sensors, remote sensing applications and AI-driven data verification. Additionally, for labour-intensive CDR pathways, OPEX support should defray labour costs through subsidies or tax incentives. OPEX and CAPEX support should be made available for the early years of project development, which is where the majority of MRV costs fall, and then taper over time. All aspects of the MRV process should be digitalised, such that so-called dMRV (digital MRV) becomes the norm.

Getting comfortable with uncertainty

Uncertainties exist regarding the safe storage of CO_2 for all CDR methods and the accuracy of MRV to detect any reversals in these CO_2 sinks. Upscaling CDR (particularly novel methods) thus becomes a question of how to become comfortable with uncertainty. To some extent this depends on the claims buyers of carbon credits want to make, which can change expectations about confidence in MRV quantification. Acceptable certainty thresholds may differ depending on the type of buyer and the use cases. Catalytic buyers, for example, may accept lower certainty or quality of carbon credits if the intended purpose of purchasing removals is for R&D demonstration support in order to stimulate demand. On the other hand, a higher certainty threshold may be required for companies that are buying CDR solely to fulfil compensatory claims. Where this is the case and underpinning science is still missing, the research community has a big role to fill knowledge gaps, evaluate existing proposals and provide best practice.

Confidence and credibility can be enhanced by establishing upper and lower uncertainty bounds for different use cases and adopting a conservative baselining approach for MRV. A probabilistic approach to uncertainty over carbon capture efficiency and the risk of reversals, underpinned by statistical analysis of observations or model results, should provide bounds for real world outcomes, ensuring that credits are issued at a conservative probability level. This could differ for each method, with policymakers establishing higher bounds for methods with geological storage where MRV is comparatively less complex, and lower bounds for open system CDR such as OAE where MRV is comparatively more complex.

Another key knowledge gap is understanding the incremental cost of MRV to reduce uncertainty. While some innovations may yield large reductions in uncertainty at minimal cost, others may be too expensive to be economically viable (whereby the additional value from selling higher credit volumes does not outweigh investment costs). From the analysis, it was observed that MRV for some of the most uncertain methods of CDR are also the most expensive (e.g. ERW and marine biomass sinking). Where MRV is costly, complex or deficient, it may lead to trade-offs between accuracy and cost, particularly if there is insufficient willingness to pay for more accurate, but more expensive MRV.

This could potentially be an issue for ERW, for example, which is currently underpinned by more minimal MRV, even though relative MRV costs are still quite high. As new, higher-standard protocols come into existence, this might impact plans to scale up, since complying with higher quality protocols might be too expensive for some companies. Although this might push up short-run MRV costs, the cost of ERW should fall over time. This is because modelling – which is generally accepted for other methods such as OAE – is not yet widely accepted within ERW MRV protocols. Instead, existing protocols – such as the one developed by Isometric – adopt a purely measurement-based approach for ERW, even though that will potentially increase costs, especially as site heterogeneity may result in oversampling. However, in-field measurements are currently needed to calibrate models and increase accuracy. Once models are calibrated, significant future cost reductions can be expected as expensive field measurement will only be needed for randomised checking for errors.

Beyond ERW, surveyed CDR suppliers were more circumspect about how additional investment could reduce uncertainty, with many unclear about the incremental cost to reduce uncertainty. Responses suggested that in some cases uncertainty could be reduced by 10% (for mineralisation) and in others by 30% or more (for OAE), although the cost of implementing this was not mentioned. Where uncertainty could be reduced it stemmed from 'investment in sensors' or 'investment to increase either accuracy of instruments with wide spatial range or sampling density of instruments with low spatial ranges'.

Where uncertainty cannot be addressed at a reasonable cost, greater deductions for credit issuance will be needed. This is just one guardrail to deal with uncertainty. Others also exist. For example, estimating uncertainty in either the quantification process or the likelihood of reversal can inform broader mechanisms for the governance of permanence, such as contribution rates to buffer pools, equivalence ratios and whether certain methods then need to procure insurance. If additional governance measures are in place this may be sufficient to manage uncertainty until new tools, knowledge and equipment are available at the right time and price.

To enhance understanding of the implications of MRV costs, detailed cost breakdowns and transparency from MRV providers are necessary. This will aid project developers in financial planning. Aligning MRV practices with the quality preferences of buyers can increase the marketability and credibility of CDR projects. Additionally, it is crucial to focus on the design and quality of MRV standards and protocols, as these define costs and ensure consistency across projects. Lastly, investing in R&D for alternative MRV methods beyond conventional mensuration can provide more cost-effective and innovative solutions.

Recommendation 4: To enhance confidence and manage uncertainties related to MRV, standard-developing organisations and jurisdictions should adopt conservative approaches to crediting, including asking whether it is too premature to credit some methods today – especially where the incremental cost of MRV to reduce uncertainties is too high. This approach could also include the use of probabilistic certainty thresholds that are tailored to, and differ for, individual CDR methods based on their use cases. Conservative discounting and baselining in addition to conventional risk management approaches such as buffer pools should be considered.

Factors influencing the approach to MRV

The survey responses provide valuable insights into how the costs of different MRV approaches influence the choice of measurement and monitoring methods. Although cost is an important consideration, it was not seen to be the overriding factor. Respondents emphasised the need to balance the overall project budget with accuracy, indicating a nuanced approach to MRV expenditure. For instance, some noted that cost primarily influenced their choice of MRV provider, while others described a blend of requirements and budget considerations. There was also a recognition of the complexities involved with projecting MRV costs, given how young so many of the companies were. As such, several respondents admitted to a lack of full understanding of cost implications.

A significant observation was that some project developers sought more extensive MRV than is outlined by current methodologies, driven by the quality preferences of buyers. This underscores the importance of aligning MRV practices with market demands. Additionally, the design and quality of standards and protocols were highlighted as crucial factors that define costs, reinforcing the need for robust frameworks to guide MRV processes. When discussing the balance of trade-offs between measurement accuracy and MRV process costs, a wide range of perspectives emerged. Many respondents stressed the importance of balancing accuracy with meeting standards and commercial needs, rather than letting cost alone drive decisions. The emphasis on maximising accuracy was evident, with six respondents specifically mentioning this priority.

Some respondents expressed concerns about potential future trade-offs, particularly as the panoply of protocols and regulatory requirements might entail different requirements and certification levels.

This anticipation of future challenges highlights the need firstly for adaptable and scalable MRV solutions that can meet evolving standards and market expectations, and secondly for clear leadership from governments through the establishment of minimum standards and quality thresholds for standard-developing organisations.

Recommendation 5: In the UK DESNZ and other relevant agencies should develop a framework that allows MRV protocols to be graded based on their performance against the minimum standards from Recommendation 1 to ensure a continuously high standard of quality and alignment with emerging market preferences for high-quality CDR. At the same time, the protocols must not be so complex that they present a barrier to achieving outcomes or so stringent that they make MRV prohibitively expensive. Where protocols are shown to be misaligned with UK best practice, MRV providers should be given time to rectify this, so that there is alignment with market demands and regulatory requirements. Ensuring adherence to a minimum standards framework could be fulfilled by an MRV regulator.

Informing assumptions for equivalence ratios

Understanding the cost of MRV for different methods can also inform academic and policy research: for example, by providing more accurate MRV costs within economic approaches for valuing temporary storage. In the absence of data, early contributions to this field assume ongoing MRV costs are 5% of the total investment for all CDR solutions (Prado and Mac Dowell, 2023). However, MRV costs vary across methods, and in almost all cases significantly exceed this number. The average MRV cost across all methods relative to the total cost of removal is 12% for the Grantham dataset, and 23% for the Frontier dataset.

Using more accurate MRV and method-specific cost information will substantially change the equivalency ratio that is used to determine the number of temporary tonnes of removed carbon needed to be stored to be equivalent to 1 tonne stored permanently. This will result in a higher ratio of temporary CDR to permanent carbon storage. Consequently, what appears to be 'cheaper' removal today actually implies large future costs when the higher costs of MRV are fully accounted for.

With governments such as the UK's considering this approach, it is critical that the assumptions are robust. Small differences in assessing MRV costs alongside normative assumptions about the social cost of carbon and future discount rates or future removal costs can imply dramatic environmental and economic implications for society (Burke and Schenuit, 2023).

Recommendation 6: Economic approaches to valuing temporary storage should move towards method-specific MRV cost assumptions. This would be an important step forward, not least because it might change perceptions on the cost-effectiveness of temporary storage versus more durable CDR.

5. Conclusion

The ability of the world to limit global temperature rise to 1.5°C this century is now increasingly reliant on the inclusion of carbon dioxide removal alongside the mitigation of further emissions. However, for society and governments to have confidence in CDR, it is critical that there is oversight of the spectrum of carbon removal and storage methods. Monitoring, reporting and verification provides this service. However, in such a nascent industry, there are many unknowns associated with the efficacy of different MRV methods, including how to strike a balance between acceptable cost, commercial needs and the accuracy of quantification.

This report has attempted to examine this question by examining how MRV costs might influence the long-run marginal costs of CDR, and what opportunities exist to reduce these costs to ensure CDR can upscale, while maintaining public acceptability and environmental integrity. The report provides an early assessment of the costs of MRV for CDR but the numbers herein only present a snapshot between the years 2022 and 2024 and must be revised over time, responding to technological and process innovation.

Until now MRV costs have been bundled within overall CDR cost estimates and there has been a dearth of granular, method-specific MRV cost data. Early contributions to this field have assumed ongoing MRV costs are 5% of the total investment for all CDR. The research presented in this report has provided updated estimates, albeit with a small sample size, of the average MRV cost across all methods, relative to the total cost of removal. For the Grantham dataset this is 12%, while for the Frontier data set it is 23%. Given the small sample size, repeating the survey with stronger and wider industry participation is a priority for future research.

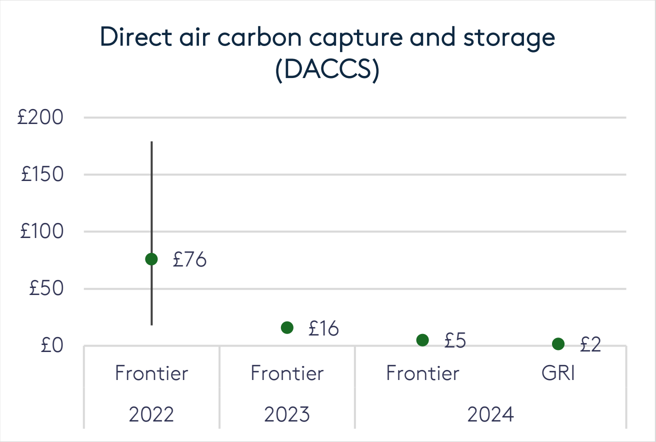
More research is needed to develop detailed method-specific MRV cost estimates and to identify (at a more granular level than presented here) which MRV processes are costly, the incremental cost to reduce uncertainty and inefficiencies, and the unknowns that will require focus and policy support.

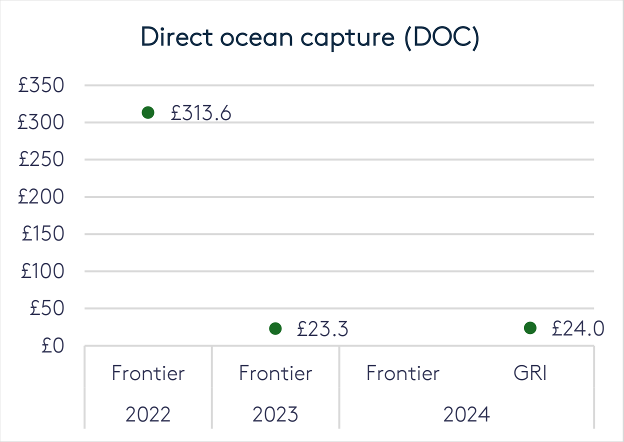
Some early commentary has been provided on the relationship between uncertainty and MRV costs. This question will require more attention, as governments are currently developing MRV standards that will need to balance accuracy (to maximise climate benefits and oversight) and the imposition of higher costs, through regulation, on companies attempting to upscale a critical industry.

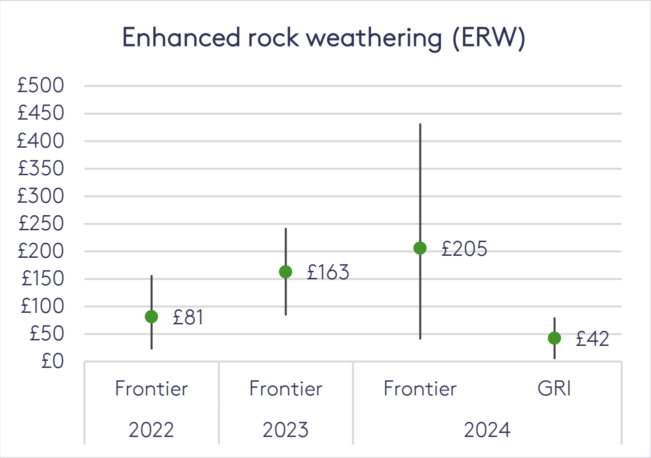
Appendix: absolute and relative costs of MRV, 2022–2024

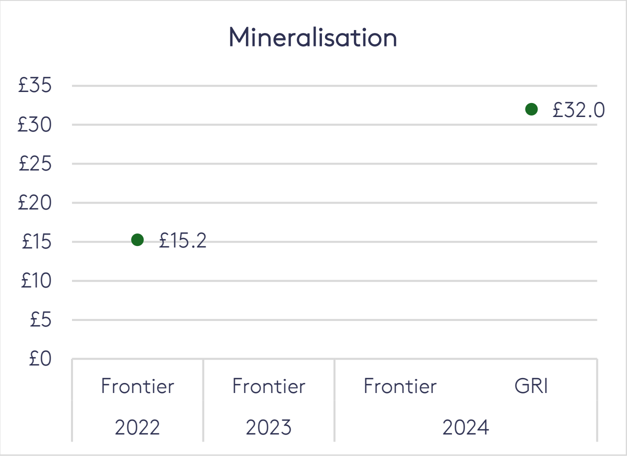
This appendix illustrates how the absolute and relative costs of MRV have changed over time by providing data from 2022–2024.

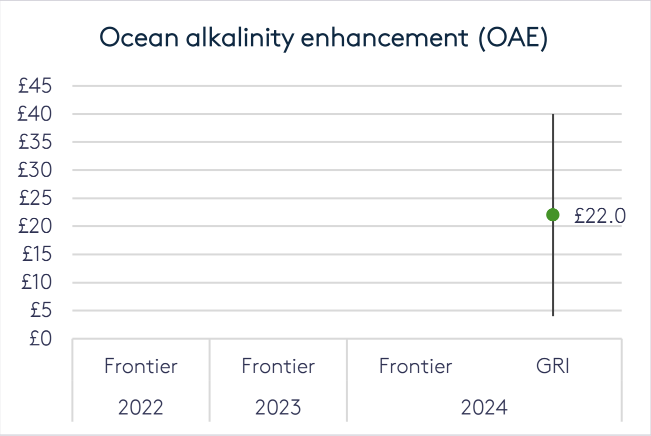
1. Absolute MRV costs over time from the two datasets: Grantham Research Institute (GRI) and Frontier (£ per tonne of carbon)


Direct air carbon capture and storage (DACCS)
£200
£150
£100
£50
£0
£76
£16
£5
£2
Frontier
Frontier
Frontier
GRI
2022
2023
2024

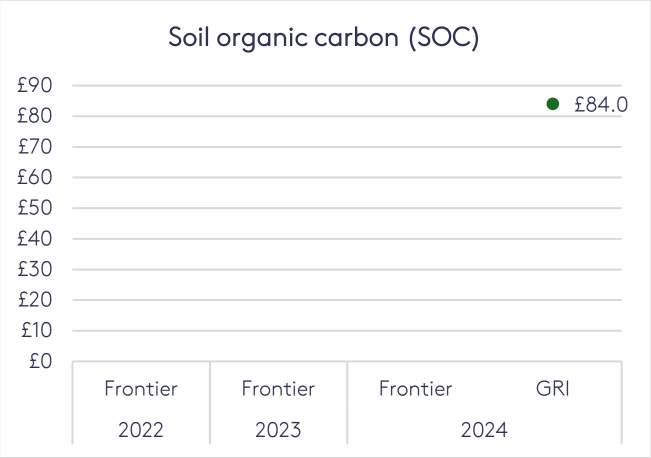

Direct ocean capture (DOC)
£350
£300
£250
£200
£150
£100
£50
£0
£313.6
£23.3
£24.0
Frontier
Frontier
Frontier
GRI
2022
2023
2024


Enhanced rock weathering (ERW)
£500
£450
£400
£350
£300
£250
£200
£150
£100
£50
£0
£81
£163
£205
£42
Frontier
Frontier
Frontier
GRI
2022
2023
2024

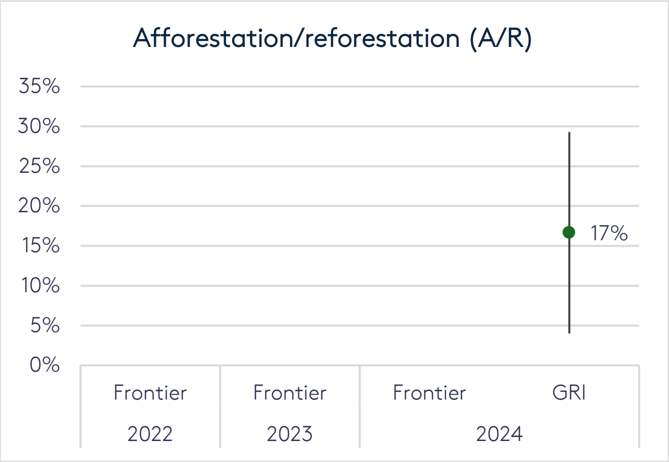

Mineralisation
£35
£30
£25
£20
£15
£10
£5
£0
£15.2
£32.0
Frontier
Frontier
Frontier
GRI
2022
2023
2024

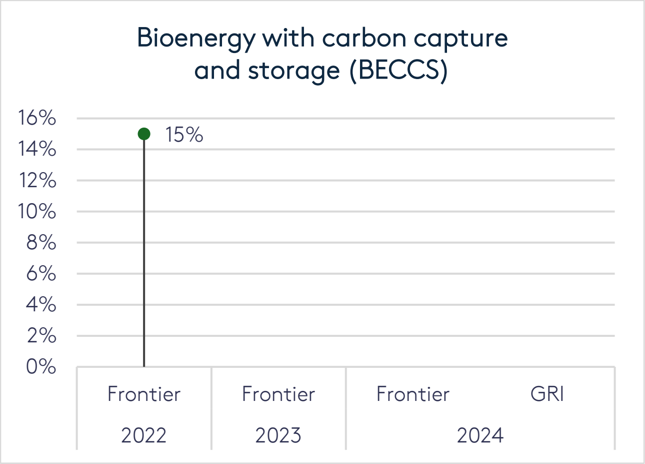

Ocean alkalinity enhancement (OAE)
£45
£40
£35
£30
£25
£20
£15
£10
£5
£0
£22.0
Frontier
Frontier
Frontier
GRI
2022
2023
2024

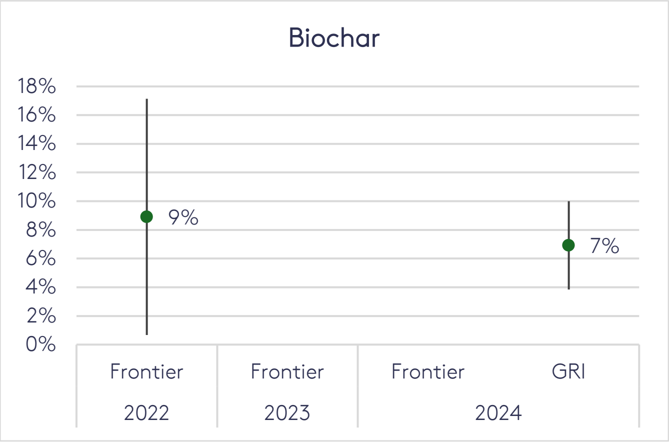

Ocean fertilisation
£1
£1
£1
£1
£0
£0
£0
£1.0
Frontier
Frontier
Frontier
GRI
2022
2023
2024

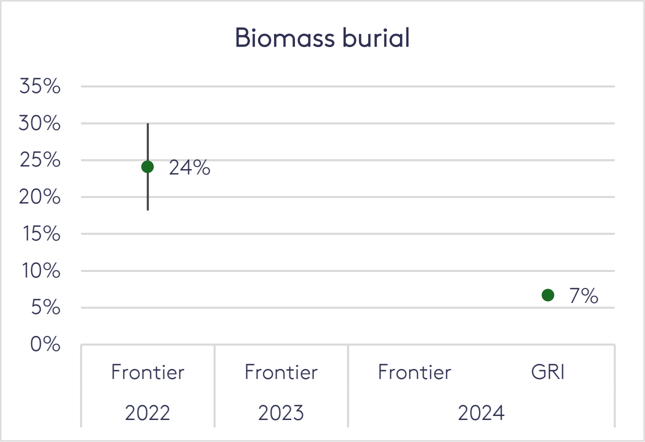

Soil organic carbon (SOC)
£90
£80
£70
£60
£50
£40
£30
£20
£10
£0
£84.0
Frontier
Frontier
Frontier
GRI
2022
2023
2024

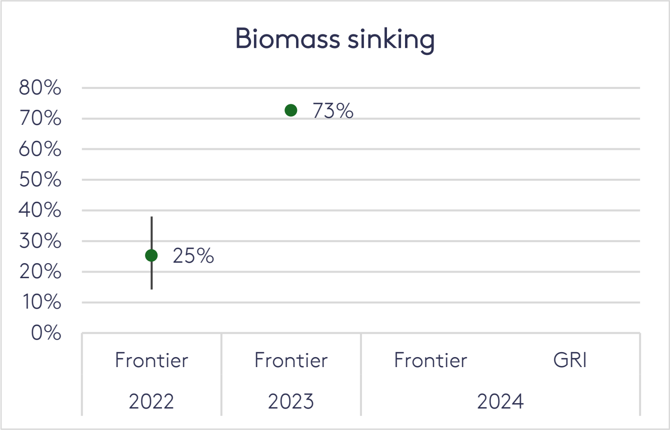
2. Relative MRV costs over time from the two datasets: Grantham Research Institute (GRI) and Frontier (% of total cost)

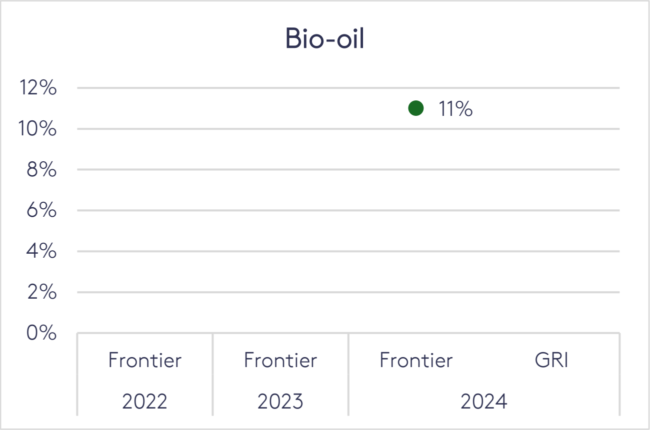


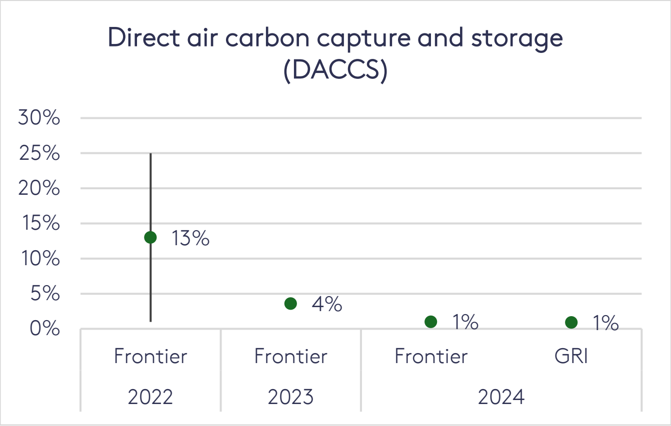


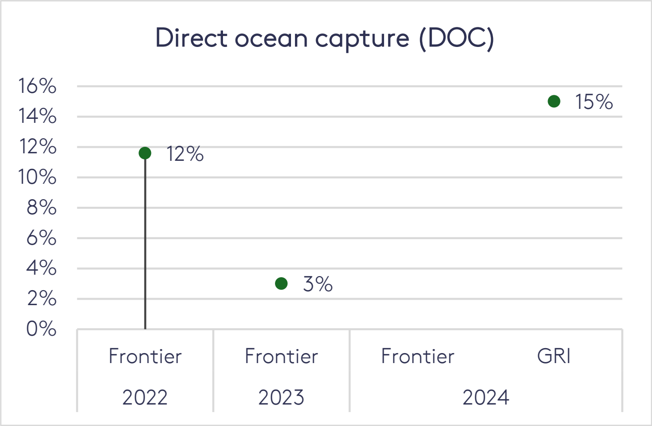


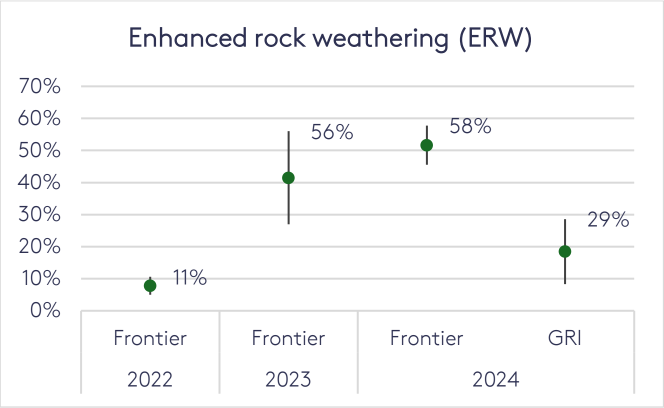


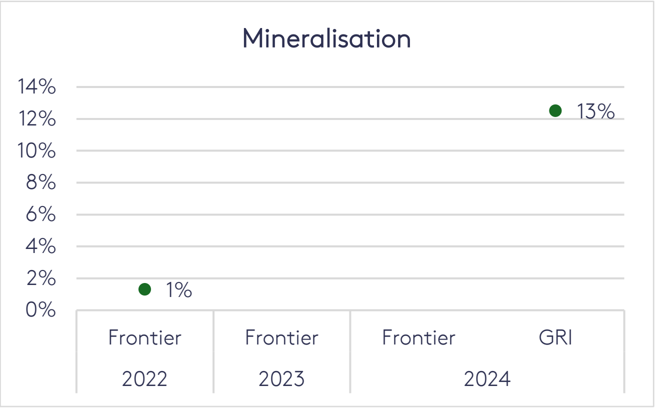


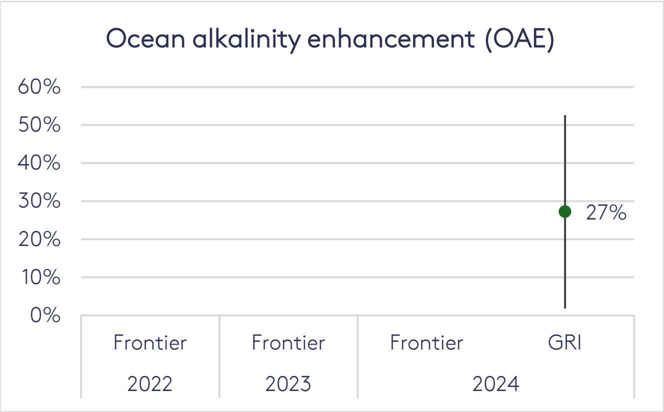


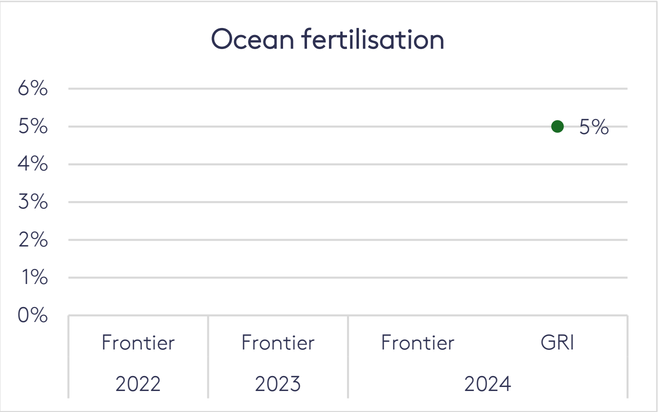


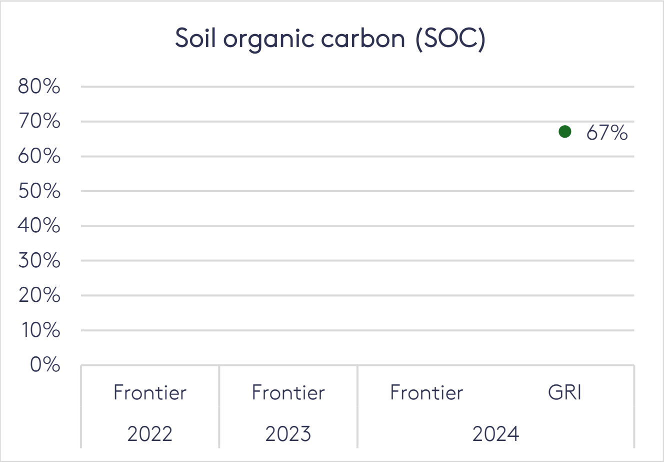



Enhanced rock weathering (ERW)
70%
60%
50%
40%
30%
20%
10%
0%
11%
56%
58%
29%
Frontier
Frontier
Frontier
GRI
2022
2023
2024


Mineralisation
14%
12%
10%
8%
6%
4%
2%
0%
1%
13%
Frontier
Frontier
Frontier
GRI
2022
2023
2024


Ocean alkalinity enhancement (OAE)
60%
50%
40%
30%
20%
10%
0%
27%
Frontier
Frontier
Frontier
GRI
2022
2023
2024


Ocean fertilisation
6%
5%
4%
3%
2%
1%
0%
5%
Frontier
Frontier
Frontier
GRI
2022
2023
2024


Soil organic carbon (SOC)
80%
70%
60%
50%
40%
30%
20%
10%
0%
67%
Frontier
Frontier
Frontier
GRI
2022
2023
2024

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