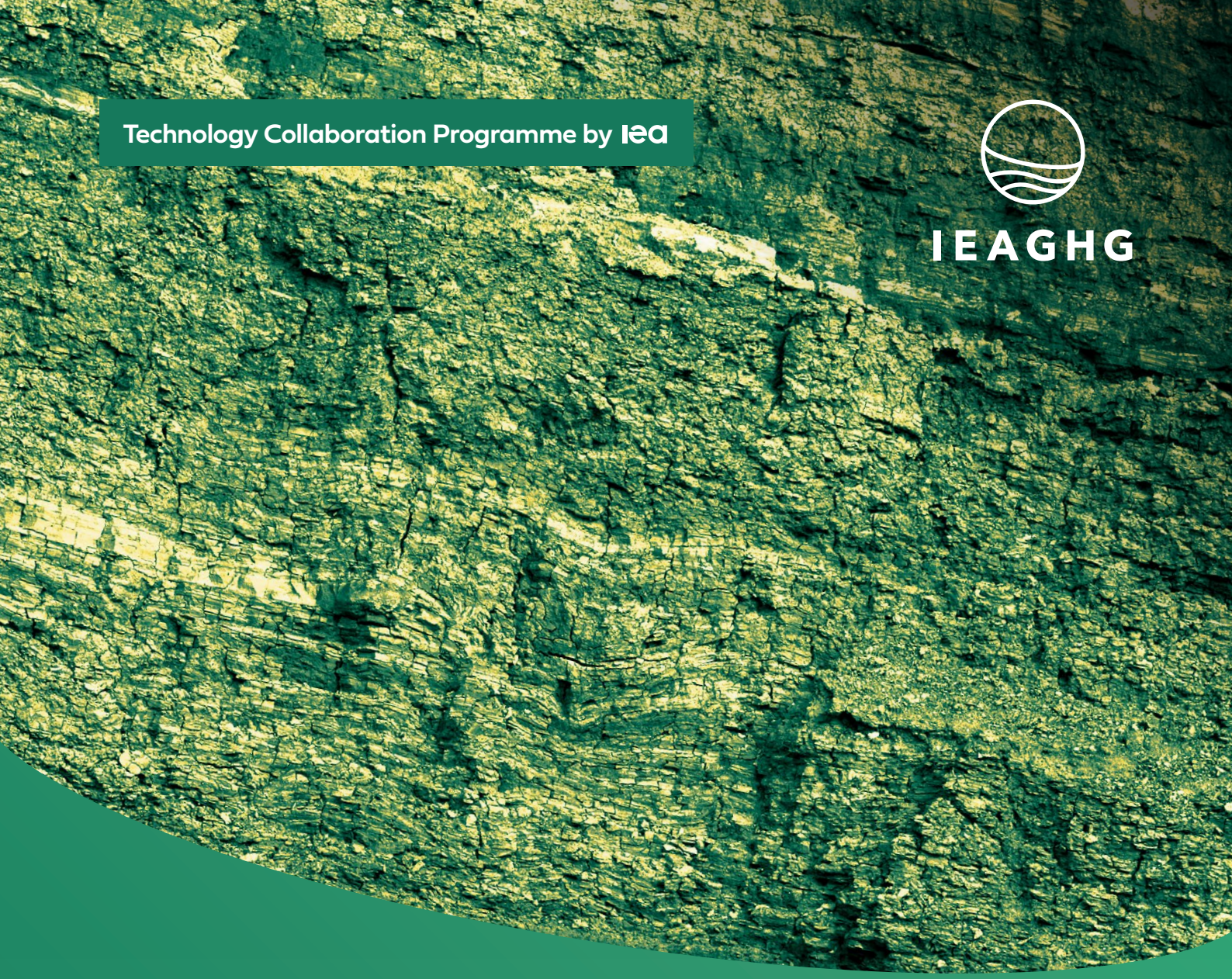

Technology Collaboration Programme by IEA

IEAGHG

IEAGHG Monitoring Selection Tool Updates 2024-2025

Technical Review 2025-TR02
August 2025
IEAGHG

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- H Taylor
- S Raveendram
- C Blackburn
- C Watson
- JM Pearce
- G Williams
- R Luckett

To ensure the quality and technical integrity of the research undertaken by IEAGHG each study is managed by an appointed IEAGHG manager. The manager for this report was Nicola Clarke.

Technical Review Overview:

IEAGHG Monitoring Selection Tool Updates (2024-2025)

2025-TR02

IEA/CON/24/307

Overview

In 2005-6 the British Geological Survey (BGS) were commissioned by IEAGHG to design a web-enabled decision support tool (subsequently called the Monitoring Selection Tool or MST in this report) to help users to select appropriate techniques to monitor a CO_2 storage site. The easy-to-use, peer-reviewed Monitoring Selection Tool, hosted by IEAGHG[1], is made up of several components:

- A knowledge base that lists the monitoring techniques and their attributes.
- An expert system that selects appropriate techniques, based on user inputs, pre-defined relationships between techniques and the attributes of each monitoring technique.
- A web-based output with links to a description of each selected technique, its limitations and applications. Case histories and references, including web links are provided.

[1] https://ieaghg.org/monitoring-selection-tool/

The MST is generic, making recommendations based on the storage scenario information supplied by the user. The MST output selects tools as essential or optional and uses a ranking system which was developed by BGS with user feedback when the tool was built and reviewed during later updates. While site- and project-specific conditions may preclude some of the techniques recommended by the MST from subsequent application, we believe its generic nature is a positive way of encouraging consideration of a wide range of techniques, and of fostering dialogue both internally within a project team and between operators and regulators. The MST originally aimed to support users in decision making.

Since its launch in 2006, the MST has regularly undergone routine maintenance and numerous updates to technique descriptions, case studies, bibliographies, content management system along with additions of resources (benchmarking, cost information), and improvements to functionality, interfacing and webpage design. The last technical update before this project was undertaken in January 2019.

When commissioning this current round of updates, IEAGHG did so in collaboration with the BGS to determine what was necessary. The following objectives were set during that consultation:

- Maintenance to ensure the long-term stability of the MST, including migration to a new server to comply with BGS' Cyber Essentials and certification
- Update of the knowledge base
- Perform a user consultation to inform recommendations for a more in-depth future update of the MST
- Draw conclusions and a set of recommendations for MST v4.

This report outlines the outcomes from this 'light touch' update to the MST undertaken by the BGS for the IEAGHG during 2024-2025. As well as the necessary maintenance of the underlying code to ensure ongoing stability and security of the tool there has been an update to the knowledge base with a view to future in-depth revisions. This included an update to the overview sections of the tool description. Looking to the future a range of stakeholder engagement exercises were performed to assess what functionality current and potential users would like to have in future updates. This included:

- Structured interviews with representatives from identified user groups of the MST
- A workshop with the IEAGHG Monitoring Network Steering Committee
- An online survey (based around outcomes from the interviews and workshop).

The results of these engagements are detailed in this report and formed the basis of the recommendations for further work. The user groups targeted for the structured interviews came from the following backgrounds: University staff and students, research organisations, field pilot or testbed site operators, and full-scale project developer/operator. This provided a wealth of information on how the MST is used, aspects that users appreciated and recommendations for future updates. The MST was described

as a unique resource providing an extensive catalogue of techniques, valued for its simplicity and ease of use.

A follow-up workshop presented the results of these interviews and further refined a list of options that were then presented as a ranking exercise to those taking the online survey. The survey respondents stated that they currently use the MST for: developing monitoring plans, teaching and learning, reviewing monitoring options, and strategic purposes. Future uses indicated continuing to use it for developing and refining monitoring plans and potential new applications e.g. evaluating individual project proposals and developing new monitoring strategies. The full outcomes of the survey and recommended enhancements are contained in this report. The overarching theme was to develop the tool to be more risk-focused. A risk-led option could help users identify relevant monitoring technologies tailored to particular site challenges. The value of providing a justification for each tool's risk score was also noted. New technologies were recommended for inclusion and the site catalogue updated.

The next steps for the monitoring tool are to:

- Promote and improve the findability of the MST. Initial data suggests that it is being used – with over 1500 views from 600 individual users during the period July 2024 to April 2025. But with a more focussed approach there could be improvements made on findability.
- Evaluate a priority list of improvements to a future update and
- Rewrite the supporting code to support longevity.

IEAGHG would like to thank the BGS team for this recent update and their thoughtful evaluation of stakeholder needs and wants regarding future revisions. The monitoring community who participated in interviews, the workshop and online survey are also thanked.

British Geological Survey

IEAGHG Monitoring Selection Tool Updates

CCS Geodisposal, Decarbonisation and Resource Management Programme

Commissioned Report CR/24/065

BRITISH GEOLOGICAL SURVEY

CCS Geodisposal, Decarbonisation and Resource Management Programme

Commissioned REPORT CR/24/065

IEAGHG Monitoring Selection Tool Updates

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Keyworth, Nottingham British Geological Survey 2025

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1 Foreword

This report is the published product of a desktop study by the British Geological Survey (BGS), The research was conducted for the IEAGHG. The project commenced in January 2024 and was completed in May 2025.

2 Acknowledgements

The authors wish to thank Nicola Clarke and Sam Neades from the IEAGHG as well as the IEAGHG Monitoring Network Steering Committee for their invaluable contributions to this report. We would also like to thank the stakeholders who generously gave their time to provide invaluable insights and advice on how to improve the IEAGHG Monitoring Selection Tool in future updates.

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4 Summary

In 2005 - 2006 the IEAGHG commissioned the British Geological Survey (BGS) to design an online Monitoring Selection Tool to help users to select appropriate techniques to monitor a CO_2 storage site. The Monitoring Selection Tool is hosted by IEAGHG on their website. The IEAGHG has supported several updates to the Monitoring Selection Tool content since its inception.

This report describes a 'light touch' update to the Monitoring Selection Tool undertaken by BGS for the IEAGHG during 2024 - 2025. The work included essential maintenance on the underlying code to ensure stability and security of the tool, and an update of the knowledge base to reflect current practice in monitoring CO_2 storage sites. The project also engaged with current and potential users of the Monitoring Selection Tool to assess possible improvements in planned future updates.

A number of code updates were implemented: The existing code for the monitoring tool, version 2.4.1, was imported to BGS's internal GitLab system to enable automatic deployment of the code and facilitate version control. The functionality for users to log in was removed, since the authentication system did not meet modern standards. This means that users cannot currently save scenarios, but other functionality of the tool remains unchanged. The currently available version is v2.5.

The Monitoring Selection Tool knowledge base was given a light-touch update to better reflect the current state of knowledge on monitoring techniques, with a view to a future in-depth revision (see recommendations). The Monitoring Selection Tool knowledge base includes a catalogue of around 40 major techniques. Where data are publicly available, each technique has a summary, detailed description, case studies and bibliography. Following stakeholder feedback the overview sections were updated for these 40 major techniques, to briefly state the main tool application, highlights/lowlights, maturity, cost range, and deployment requirements. The Monitoring Selection Tool knowledge base also includes a list of CO_2 storage sites ranging from testbed to full commercial scale, for this part of the knowledge base, broken links were replaced/removed.

Stakeholder engagement was undertaken on the current online version of the Monitoring Selection Tool (MST) to assess what functionality current and potential users would like to have after future updates. Stakeholder engagement included structured interviews with representatives from the identified user groups of the Monitoring Selection Tool, a workshop with the IEAGHG Monitoring Network Steering Committee and an online survey. Feedback on the value of the tool and its ease of use and simplicity was overwhelmingly positive, and it was recommended to ensure simplicity and ease of use remained a priority. Maintaining the tool catalogue across the full range of Technology Readiness Levels was also supported.

The priorities for future updates are as follows:

- Rewrite underlying code to support longevity
- Develop a risk-led approach to reflect current practices
- Undertake user interface (UI) enhancements to align with modern expectations
- Promote and improve findability of the MST
- Add new monitoring techniques & update selection tables
- Update structure and content of the tool catalogue for consistency, add new information on existing tools
- Add new sites and case studies to include more information on tool deployment and successes to enhance decision support aspects
- Provide additional clarity on ranking of monitoring tools
- Undertake user experience (UX) enhancements to improve functionality (with user testing on UX, UI and technical aspects)
- Enable more user input to the technical content

5 Introduction

In 2005 - 6 the British Geological Survey were asked by IEAGHG to design a web-enabled decision support tool (subsequently called the Monitoring Selection Tool or MST in this report) to help users to select appropriate techniques to monitor a CO_2 storage site. The Monitoring Selection Tool, hosted by IEAGHG, is made up of several components:

- A knowledge base that lists the monitoring techniques and their attributes
- An expert system that selects appropriate techniques, based on user inputs, pre-defined relationships between techniques and the attributes of each monitoring technique
- A web-based output with links to a description of each selected technique, its limitations and applications. Case histories and references, including web links are provided.

The Monitoring Selection Tool is generic, making recommendations based on the storage scenario information supplied by the user. The MST output selects tools as essential or optional and uses a ranking system which was developed by BGS with user feedback when the tool was built and reviewed during later updates. While site- and project-specific conditions may preclude some of the techniques recommended by the MST from subsequent application, we believe its generic nature is a positive way of encouraging consideration of a wide range of techniques, and of fostering dialogue both internally within a project team and between operators and regulators. The MST originally aimed to support users in decision making.

Since its launch in 2006, the MST has regularly undergone routine maintenance and numerous updates to technique descriptions, case studies, bibliographies, content management system along with additions of resources (benchmarking, cost information), and improvements to functionality, interfacing and webpage design. The last technical update before this project was undertaken in January 2019. The current live version is v2.5 (Figure 1).

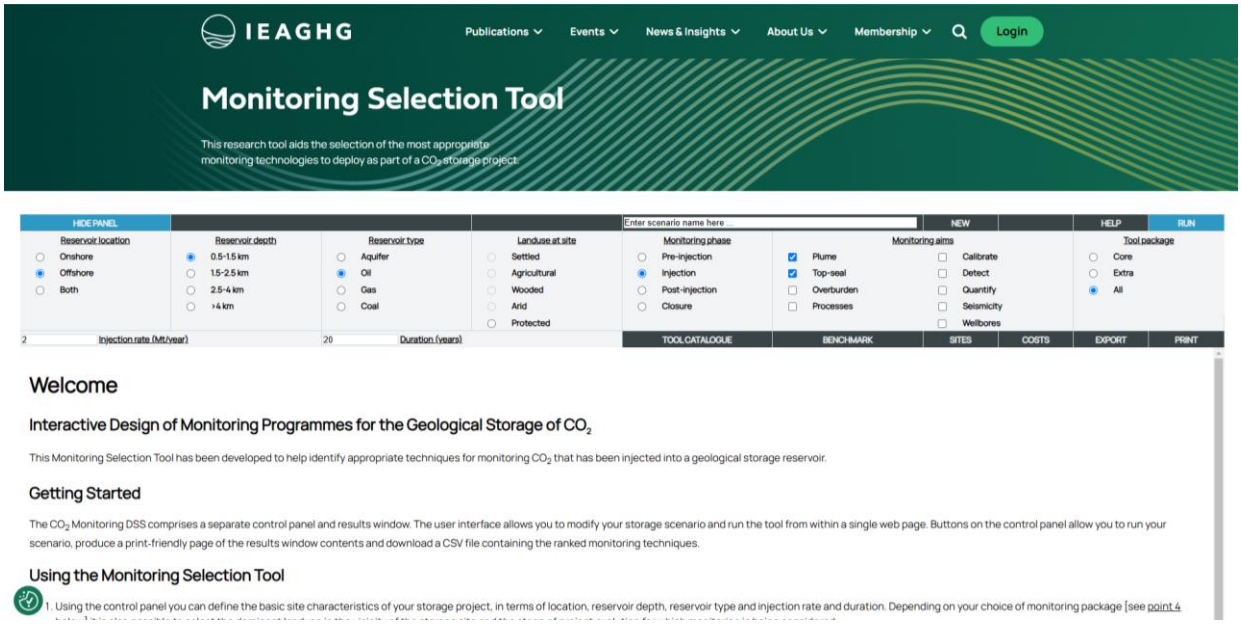


Figure 1 Monitoring Selection Tool v2.5 landing page, accessed from IEAGHG, 2025

6 Maintenance changes

Maintenance updates have been performed to ensure the ongoing stability and security of the Monitoring Selection Tool, and to enable user access to continue smoothly. There were two immediate issues:

- Essential maintenance, including migrating the Monitoring Selection Tool to a new Linux server before summer 2024 to comply with BGS's Cyber Essentials Plus certification (NCSC 2024)
- The Monitoring Tool is scripted in PHP which no longer meets BGS standards.

The decision to migrate the Monitoring Selection Tool to its new server without re-scripting at this stage means the MST needs to be hosted on a dedicated virtual server as a standalone web application. This isolates it from other BGS servers, which should also prevent unexpected downtime caused by routine roll-out of BGS security updates.

The MST needed to be integrated/remapped to maintain functionality, visibility (using existing URLs) and compatibility. The current PHP-based construction restricts the extent to which page styling can be changed, but the appearance of the MST has been adjusted to better align with the new IEAGHG website. A summary of changes is provided in this section.

6.1 SUMMARY OF CHANGES MADE TO THE CODE

6.1.1 Development

The existing code for the MST v2.4.1 was imported to BGS's internal GitLab system. GitLab is a version control system that facilitates good practice in software development. It also manages automatic deployment of the underlying code, below. Prior to version 2.4.1 there was no formal version control. The move to GitLab will aid future development of the tool.

Rescripting in HTML or Java is not part of the current work, but the current PHP version has been updated to ensure the Monitoring Selection Tool continues to function and complies with BGS standards.

6.1.2 Deployment

Previously, the application was deployed manually on a dedicated virtual machine (VM). The operating system of that VM was deprecated within BGS and so the code, files and libraries that the Monitoring Selection Tool needs to run were bundled together on a virtual machine (also known as containerisation). The containerised tool can now be deployed automatically by GitLab. Changes to the software can also now be tested on internal development systems before being deployed on the external-facing system for use by IEAGHG systems.

6.1.3 Functionality

The functionality and database tables that allowed users to register and save scenarios has been removed. The user authentication method had become insecure by modern standards, and a more secure system would require significant development time. However, a consequence of this is that users can no longer save their MST outputs. The value to users being able to save their outputs and to use these as an input for scenario iteration should be revisited with user groups during future development of the MST.

During maintenance, the font used in the HTML pages has also been changed, to better match that used on the IEAGHG website.

7 Technical content changes

During the current project, BGS updated the Monitoring Selection Tool knowledge base using publicly available information from conferences, journals and reports, including IEAGHG reports. In recent years industry experience has grown as projects are developed, permitted and implemented, which created an opportunity for a light touch review and update to the knowledge base. Current practices at existing testbed, pilot, demonstration or full-scale storage sites are considered. The case studies were updated to reflect current practice; this is fundamental to maintaining the relevance and applicability of the MST. A summary of the changes is given in this section.

For each monitoring technique, the catalogue entry in the knowledge base comprises the following sections: overview; full description; indicative costs; case studies; bibliography. It is worth noting that feedback from users for future updates as described in this report (sections 8, 9, 10) was sought before the light-touch update to the technical content of the MST described in this section was rolled out online.

The current update covered all 40 techniques in the knowledge base tool catalogue, including monitoring the deep subsurface for model conformity as well as deep, shallow and environmental geophysical and geochemical monitoring for assurance and licensing for offshore and onshore CO_2 storage settings. New techniques could not be added during this light touch review as this would require updates to the selection/ranking aspect including the underlying code, and this was outside the scope of the current update. Following stakeholder feedback obtained during this project, the overview sections for each technique were updated to briefly state the tool application, highlights/lowlights, maturity, cost range and deployment requirements.

The knowledge base includes a ‘benchmark’ page which provides a matrix of the monitoring techniques and the storage sites where they have been deployed. A list of storage ‘sites’ and basic data such as storage type, depth, total injected mass of CO_2 and duration, and a short description, are also provided in the knowledge base. A light touch update to storage site information was undertaken where data were easily accessible to replace broken links and update the quantities of injected CO_2.

As of March 2025, there are multiple new sites in construction or operation and at least a selection of these should be added in future updates. The application of monitoring technologies at these sites should be included in a future update to the Monitoring Selection Tool, where such data are available.

7.1 MONITORING TECHNIQUE OVERVIEW AND FULL DESCRIPTIONS

For each technique, the overview section provides key information about the technique and how it can contribute to a site monitoring plan based on current practice. During the current update, in response to stakeholder feedback, the overview sections for each technique were updated with new subheadings to briefly state the tool application, highlights/lowlights, maturity, indicative cost ranges, and deployment requirements. This update provides a more easily digestible summary on the first page for each technique.

7.2 NEW CASE STUDIES

During the 2024 CO_2GeoNet Open Forum in Venice, a Danish case study on sparse 3D seismic acquisition was offered. The contact provided a short (few pages) description which was then summarised and checked with the contact before being added to the 3D seismic catalogue page.

During the CO_2GeoNet Open Forum in Venice, a case study using muons to monitor a CO_2 testbed was presented. The contact was invited to provide more information such that a case study could be added to this catalogue page as no examples were included at the last update.

BGS has recently undertaken a scoping study for a UK CO_2 storage research facility (BGS, 2022) and information collated about monitoring techniques has informed updates to the knowledge base pages.

7.3 INDICATIVE COSTS

Costs for onshore and offshore wells, seismic surveys, groundwater analysis, and various other survey techniques were updated where information was available. These data have been fed into the indicative cost sections.

7.4 BIBLIOGRAPHY

The reference sections were checked, a small number of additional references were added and broken links to supporting information were replaced or deleted. Papers that were stated as 'in press' were updated with the correct attribution information and DOIs were added where available.

7.5 STORAGE SITES

The list of storage sites was not updated since this was outside the current scope and will require considerable resource to undertake. Broken links were removed or replaced in the current storage site list, and where available, quantities for injected CO_2 were updated.

For future updates, new CO_2 storage sites should be added. GCCSI (2024) provides an updated list of larger capture facilities indicting that, as of November 2024, globally there were 50 projects with operational status and 44 under construction. There may also be new pilot and testbed sites which can provide information on monitoring techniques. For example, ECCSEL (2025) has five testbeds that are not currently included in the MST site catalogue. The current site catalogue contains 26 sites, some of which have now completed operations. During future MST updates it will be necessary to decide which sites provide the most relevant information on monitoring technologies, and which make all the required data available, to support a decision on which should be added to the site catalogue.

8 User interview findings

A series of structured user interviews was conducted with stakeholders who had previously used or expressed an interest in the Monitoring Selection Tool, or with companies that were directly involved in site development. The aim of the interviews was to gain a broad understanding of what additional functionality and technical content existing and potential users would like to see from a future update to the knowledge base and user experience/Graphical User Interface aspects.

The focus of the interview was to assess if/how users applied the tool to their work, if the results were useful, how easy it is to apply the tool to their desired scenario/site, and how easy it is for users to explore the different techniques and download the data.

Interviews were conducted with several users with slight adjustments made to accommodate different levels of experience with the MST and domain knowledge.

The potential users of the IEAGHG monitoring tool span diverse backgrounds, interests, skills and experiences (e.g. regulators, students, researchers, storage operators, policy makers). Informal discussions suggested the main users were most likely to be project developers,

researchers and taught students. Focusing on the key user groups and their objectives will be important for future updates of the MST.

The findings from the first few interviews were then used to inform discussions at a workshop with the IEAGHG Monitoring Network Steering Committee. The findings from both the interviews and the workshop fed into the design of an online survey which gathered information from a larger number of existing and potential users.

8.1 USER INTERVIEWS

Eight interviews were conducted. Interview requests were emailed to a selection of contacts, followed by a link to the MST and the interview questions. Some interviewees had previously used the MST, while others had only looked at the MST when sent the pre-interview information and questions. Most interviews had two institute representatives responding to the request. Each interview took between 40 and 60 minutes.

An overview of the user groups approached is provided in Table 1.

Table 1 User group interviews

User type	User goals	Skills and experience
Taught university students (one interview with teaching staff)	Test out different scenarios, use selection option, and learn more about tools	Technical background but not necessarily in CCS
Research organisation (two interviews)	Provide list of potential tools from which to make own selection	Background in CCS or new to the field with a technical background
Field pilot or testbed site operator (three interviews)	See latest developments and what could be tested at their site. Understand where tools have been applied and why they have been unsuccessful to drive improvement	Typically, years of experience in CCS or the subsurface
Full scale project developer/operator (two interviews with research team members)	List of options for monitoring to review (especially for new operators)	Typically, years of experience in CCS or the subsurface though there could be those newer to CCS as industry develops (interviewees had years' of experience in CCS)

8.2 RESULTS FROM USER INTERVIEWS

8.2.1 University students

University teaching staff interviewed reported using the Monitoring Selection Tool extensively during teaching. Students are given fictitious case studies and then use the MST to support discussion and to develop a monitoring plan.

The interviewed teaching staff reported that they found the tool unique and useful in providing background information on all the tools. They said the tool was simple, easy to use and the terminology is well explained. They described the tool as very useful and intuitive to understand and recommend suitable technologies for CO_2 monitoring. The teaching staff felt that having

information on techniques at all Technology Readiness Levels (TRL) was a positive aspect of the MST.

The teaching staff recommended that, in a future update, the MST should become risk-led and more linked to regulations where possible. They suggested that user input should start with a risk catalogue that allowed them to consider the maturity of understanding of risks. Monitoring techniques should be specifically used to remediate risks. The teaching staff also indicated that US regulations start from groundwater protection regulations and that it would be helpful to have a link between the monitoring techniques recommended by the MST and regulations. They noted that in the CO_2 storage community, there is now a strong emphasis on pressure monitoring (including history matching) and that this doesn't really come across in the current version of the MST. The teaching staff indicated that wells also need to play a larger role in a risk-led MST. They also noted that the USA has a lot of legacy wells, and these learnings could feed into the future MST update.

The teaching staff noted that being able to iterate scenarios would be a welcome update. Their research group has an online tool where you can export the outputs for use as an input file, this means that users can update and develop scenarios. This would be beneficial in a future update of the MST since users could then redo the scenario as they learn more about the site over time and this would help in thinking about maturity of understanding of a site.

Clarity of information in the MST was viewed positively by the teaching staff. They noted that the US Environmental Protection Agency tells you what you need to do to meet regulatory requirements and then provides examples to aid understanding. They recommended that the updated MST adopt a similar approach.

Costs were indicated as an important factor since this can help users decide if they really need to use a particular tool.

The teaching staff also noted that the case studies need to be updated.

The ability for users to report issues with online webtools was also highlighted as important by the teaching staff.

8.2.2 Research organisations

The researchers interviewed indicated that the Monitoring Selection Tool was a good initiative since it provided all the information about monitoring techniques in one place. The researchers said they used the MST to provide an overview of available monitoring techniques and a list of potential techniques from which to select. They were positive about the tool, describing it as useful and easy to use.

The researchers were keen to see more examples where monitoring techniques had been applied and in particular where the techniques formed part of successful storage permit applications. The researchers said they thought new project operators would find it useful to understand what governments have approved in terms of monitoring for storage licences. They noted that globally, there are multiple approved storage permits, and some are public domain which could be added to the MST in future updates. The researchers asked that the MST was extended to include more case studies from full scale projects and monitoring programmes and suggested that regulatory aspects could be included in the selection criteria. The researchers asked for more papers to be included to show where techniques had been applied and said that it would be nice to have a constantly updated reference list (e.g. weekly). They also observed that it would be useful to have more information on costs.

For the scenario generator, the researchers indicated that more flexibility would be welcome. This could include more lithologies, inputs on the over- and under-burden and geomechanical aspects such as current reservoir pressure. They considered monitoring of pressure and temperature important and felt that the importance of pressure monitoring was not really emphasised sufficiently in the current version. The researchers also noted that monitoring aims

can change with time and that currently the MST didn't capture this evolution of monitoring. The researchers said it would be useful to be able to save and share outputs from MST.

The ranked tool output was viewed positively by the researchers, and the fact that some techniques were always recommended was viewed as a strength since it told the users which techniques they must consider. The researchers were interested in why some techniques are considered unsuitable were ranked low. For example, it could be explained that seismic techniques are not particularly useful to quantify CO_2 in depleted gas field stores. The researchers also asked if the reasons why techniques were given a high or low ranking could be more explicit, though they did note this might make the MST more complicated to use and reiterated that the simplicity and ease of use of the MST is valuable to them.

The interviewed researchers noted that the MST is currently hard to find online and recommended promoting it more, e.g. at relevant conferences.

8.2.3 Field pilot or testbed site operators

The Monitoring Selection Tool was viewed as a unique resource. The field site operators interviewed said they use the knowledge base, including the technique catalogue and the benchmark page. The field site operators also said that they recommended the MST for education and coursework to their contacts, and as an initial go-to resource to review a range of techniques. The field site operators also recommend the MST to contacts in commercial sectors as a resource to support consideration of how to monitor for various risks. The MST was described as beneficial and 'extremely useful to have a simple tool for selecting monitoring technologies.' The field site operators thought the MST could support discussion with regulators about what monitoring can realistically deliver. The interviewees indicated that the MST is useful in providing an overview of CCS monitoring, and that the tool descriptions were useful. Overall, the field site operators viewed the MST very positively and said it would be good to raise awareness.

The field site operators said it was good to see techniques at all TRL represented in the MST. They highlighted that being able to see lower TRL techniques helped them identify techniques that could be commercialised at their site or were likely to become available during operational lifetimes. The wide range of techniques in the knowledgebase was viewed positively since this meant that users could view tools which are less well known and think about how to use them.

The field site operators suggested the monitoring aims should be simplified and more explicitly linked to risk. During one interview it was suggested that the future update could consider that the aim of monitoring is usually focused on containment, assurance, performance: containment to check CO_2 is staying where it should; assurance for local population; and performance and conformance look at the reservoir response and how well the resource is being used, especially if constrained. They suggested that during the update the team should think about who uses the monitoring information i.e. operators, regulators and to break the information into those three main monitoring aims and to then give relative importance of the tools for each aim of these users. Similarly, during another interview the field site operator said there were too many options for monitoring aims, and they were only interested in monitoring for operational assurance and location of the CO_2 plume, and also environmental monitoring. The interviewees asked if regulations could be accommodated, for example if you indicated the location of your storage site, would that produce a list of techniques that it was compulsory to use?

The field site operators felt the MST should provide information on tools so that the user can make decisions (e.g. cost, technical maturity).

It was recommended that future updates should include more on the practicalities of monitoring technique deployment. This included being able to specify the dimensions of the site to be monitored and costs for techniques. The interviewees were keen to consider how surface conditions (e.g. swamps) or access to wells would influence the monitoring programme. It

should be more clearly specified if a technique was used for permanent monitoring or repeat surveys.

The interviewees were very interested in being able to understand if a monitoring technique would work at their site, for example, if ground conditions might mean that at technique could not be applied. They asked for references to be added so site developers could also see where and why tools were unsuccessfully applied. The field site operators felt that knowing that a particular technique had been successfully applied at five or six other sites would help operator confidence and could facilitate collaboration where site operators could compare results.

One interviewee indicated that they liked to take the approach of finding combinations of tools that have different strengths with respect to imaging over different ranges of pore space saturations e.g. combining electrical resistivity with seismic techniques. It was recommended that in future updates the complementarity of tools was included.

In the knowledge base, field site operators recommended that a succinct summary including TRL and a picture at the top would be beneficial. This might be accessed from the field for example.

The field site operators wanted more opportunities to vary the input and to see how this affected the output of the MST. They also wanted to better understand why a monitoring technique was selected. The field site operators also noted it would be good to be able to add tools to the scenarios in the middle of the storage project i.e. the opportunity to iterate as the site evolved and new techniques became available.

The interviewees were interested in developing monitoring techniques and application of supporting technologies. They asked if the application of machine learning to monitoring techniques (e.g. plume modelling) would be included in future updates. They also recommended thinking about adding tools that are being adapted for CCS (e.g. wearable detectors with GPS). They also recommended that pre-commercial systems should be identified and maybe recommended separately than the systems that are tried and tested in the environment of deployment.

Interviewees noted that seismic techniques have developed considerably and that the MST doesn't really reflect this. They also noted that some tools are so standard, e.g. wireline logging, that commercial companies might not even think of these as monitoring, they are just part of business as usual, and yet these techniques might be the most useful.

In terms of prioritising content update, field site operators highlighted cost as the primary concern. However, they also asked for updates to the bibliography (noting that some papers they had expected to see were not included), and the case studies.

User input was also discussed with the suggestion that future updates could potentially track how people used the MST (e.g. which pages and references they used) to help prioritise updates. One interviewee asked if searches could be given an identifier so that the keywords the user entered and their search result could be compared with the MST knowledge base to see if additional material or keywords should be added. Field site operators also supported users being able to recommend new monitoring techniques and references which could then be reviewed and added to the MST.

In terms of user experience field site operators viewed the MST positively given its simplicity. However, using red for techniques selected as 'core' was questioned.

8.2.4 Research teams at storage developer companies

Storage project developers were contacted and those who responded (including after internal checking for the most suitable contacts) were mainly staff from their research teams.

The interviewed researchers at storage developer companies appreciated the benchmark page, and also the case studies and bibliography. They observed that the Monitoring Selection Tool

was too generic for storage operators to use for their own sites, however they didn't recommend that the MST should become that detailed since all operators have their own internal processes. The interviewees observed that researchers have a different approach to those in operations who would be focused specifically on their site. The researchers said that having an up-to-date repository was very helpful for them to see what techniques are being developed. They were focused on techniques that could be applied at commercial scale. The overview of monitoring techniques and the catalogue of monitoring techniques was viewed positively. The interviewees did think that the MST could be useful for new storage operators to provide an overview and highlight knowledge gaps and noted that there are only a few companies who do CCS now and this needs to change to meet the global deployment scale that's needed to tackle the climate challenge.

The researchers recommended that the MST should be more risk-led instead of environment-led. They recommended starting from the point of why a site is monitored, and to consider potential risks and how monitoring would identify a risk had materialised. From their perspective monitoring techniques are selected to help diagnose issues. During one interview the researchers said they would like to see something more visual in a future update of the MST e.g. you follow the threat branches of the risk bowtie and when you click on the barriers (e.g. 3D seismic) you get the information about that monitoring technique.

One interviewee described their company approach; they start by considering all credible risks and their team develops the premise for the site monitoring programme on that basis. Individual threat branches in the bowtie are independent. A leakage pathway might be a combination of multiple branches (e.g. migration into overlying layers that then reaches an old well). Monitoring techniques that are relevant for a particular risk are then selected. They indicated that the bowtie is a useful approach to think about risk and a useful communication tool.

The researchers recommended that evolution in monitoring programmes should be reflected as understanding of the site develops and the risk profile changes. As more is learned about the storage site, the risk profile is updated leaving only credible risks remaining. If new risks are identified, then more monitoring will be added. As risks are determined to be sufficiently minimal then some monitoring may be discontinued. Evolution of a monitoring programme includes down-selection where tools that are not cost effective or efficient are removed.

Interviewees observed that being able to see how the MST output varied if you made small adjustments to the scenario would be interesting.

It was also noted that the storage user input included storage depths that might be too great and so might not reflect sites typically of commercial interest.

Researchers indicated that pressure monitoring was not sufficiently explored. During one interview it was suggested adding the low TRL technique of using pressure pulses to monitor between wells. Fibre optics were highlighted as a developing technology that is missing from the MST. During one interview the researchers indicated that they felt fibre optics were still developing and that challenges remained including automation of real-time data analysis, machine learning to support real-time processing, and integration with other tools. A case study of using fibre optics for microseismic was offered.

The researchers suggested that to improve the usefulness of the benchmark page, more deployment information should be added: The researchers requested that the scale of application, frequency of repeat surveys, and success rate of monitoring techniques should be clearer since these deployment aspects are a key factor in decisions to use a monitoring technique. They also highlighted considerations of well access. They recommended building on knowledge from case studies more, since there are many more examples available than currently included in the MST. The interviewees wanted to understand where monitoring techniques had successfully been applied and wanted the bibliography to be extended to allow more thorough exploration of tools of interest. The interviewed researchers indicated it would be good to be clearer on the complementarity and potential suites of techniques to avoid reliance

on one type of data. Researchers were keen to see lower TRL options included with their limitations clearly stated. The researchers suggested adding a link to the STEMM-CCS environmental monitoring tool

8.3 SUMMARY OF OUTCOMES FROM USER INTERVIEWS

The user interviews provided a wealth of information on how the Monitoring Selection Tool is used, aspects that users appreciated, and recommendations for future updates.

The MST was described as a unique resource providing an extensive catalogue of techniques. The MST was valued for its extensive knowledge base of techniques and its simplicity and ease of use. Maintaining a catalogue of techniques of all TRL was supported and it was noted that low TRL techniques for development could be identified and collaboration between sites testing techniques could be fostered. The MST was used to support developing a monitoring plan.

A recommendation from all user group interviewees was to develop a more risk-led approach. This should be kept simple. Users recommended keeping the MST tool simple and focusing on reasons for monitoring storage sites. Consider who uses the information; operator, regulator, researchers etc and their objectives. Consider what are the common risks for storage and how to monitor for them. The updated MST should accommodate how the tools are used to respond to identified risks and monitoring aims (e.g. containment, assurance, performance). Users commented that there are currently too many monitoring aims and this should be simplified.

Users were keen to see regulations accommodated in the updated MST. This could include understanding what risks have to be monitored depending on the regulatory regime in place. To improve confidence in monitoring techniques, case studies showing where techniques have worked is valuable. This is particularly true where sites have a storage licence since this shows what has been approved by regulators.

An important recommendation was to ensure the MST provides the information that the user needs to make decisions on their monitoring programme (costs and other practical deployment aspects, conditions where there have been successes and failures).

It was highlighted that monitoring programmes for a site will evolve over time as understanding of the site and risk profile changes. New tools will also come to market. It was recommended that this evolution be accommodated by future updates to the MST. Users were also interested in the MST providing information that would allow development of suites of tools including for contingency monitoring and allowing for the complementarity of techniques.

The importance of effective communication on risk and monitoring was highlighted. It was suggested that making the MST more visual to follow the risk management journey could be considered.

Users wanted to be able to vary the scenarios and see how changes to input affected the output. The ability to save and iterate scenarios was requested. Users also asked for more information on why techniques are selected or not. Descriptions of previous successes and failures of tools is valuable information to support decision making for a specific site.

For the storage scenarios, it was suggested that users could better define the over- and under-burden, to address geomechanical aspects such as responses to pressure build-up. However, the MST should not be made overcomplicated.

Users observed that the case studies, costs and references all need updating and asked if these could be more regularly updated in future to reflect the burgeoning number of storage licences and sites.

Monitoring techniques in the knowledge base that need a more substantial review included seismics (the tools have developed significantly since the MST was introduced) and pressure (of much more interest than when MST was introduced). Fibre optic techniques were highlighted as missing. Techniques that could be adapted (e.g. wearable sensors) could be

included. Supporting techniques such as machine learning were also recommended for inclusion in future updates.

To improve user experience, it was recommended to provide a summary of each tool upfront (including key uses and TRL) with a picture. Then a more extensive description with case studies and references to enable the user to explore to their desired level of understanding.

Users recommended more promotion of the Monitoring Tool online and at conferences. Enhance the discoverability of the tool through Search Engine Optimisation.

Maintaining an easy route for users to recommend additional tools, case studies and references for review was highlighted. Interviewees also suggested that the updated MST could capture which areas of the MST are used most (possibly with information on the users' background)

9 Workshop with IEAGHG Monitoring Network Steering Committee

After the first few user interviews had been completed, a workshop with the IEAGHG Monitoring Network Steering Committee was convened to understand what they see as top priorities to improve the Monitoring Selection Tool in future updates.

9.1 INTRODUCTION TO THE WORKSHOP

A brief introduction was given to share the outcomes from some of the stakeholder interviews. This included sharing the user groups interviewed (research institutes, CCS developer companies and university teaching staff). Feedback from the first interviews was strongly positive indicating the tool was a valuable resource.

The outcomes of the interviews that had taken place ahead of the workshop (Section 8) were used to produce a list of potential aspects to update and the workshop attendees were invited to discuss how proposed updates might be implemented. The topics raised for discussion included making the MST more risk-led, enhancing the knowledgebase including adding more on deployment aspects and strengths/weaknesses of each monitoring technique, updates to case studies and bibliography, expanding on justifications of why techniques were identified as core or contraindicated, allowing more flexibility in storage scenarios, and making the tool more visual.

9.2 WORKSHOP DISCUSSIONS

The workshop attendees were asked to provide their insights into the criteria used by the MST to select monitoring techniques as 'core' or 'optional'. The workshop attendees highlighted that pressure was not given sufficient attention. The area of interest (i.e. areal extent) was also considered to be missing.

From the first few user interviews, the idea of making the MST more risk-led had emerged and workshop attendees were asked what this might look like in practice. The attendees indicated that risk was considered to be additional to the current list of monitoring aims and that the tool should "use the word risk". Common regulatory drivers could be included but the MST should be kept simple and allow people to focus in on risks identified in their jurisdictions.

Accommodating evolution of the monitoring programme was discussed. Including a timeline tool with different programmes is too complicated and the simplicity of the MST is valuable. Down-selection is not a straightforward exercise and requires application of human expertise.

During the interviews, users requested that there should be enough information to understand how the selection/ranking is done and, in particular, why a tool is not selected. The workshop attendees supported providing more information on this, and also suggested that a few key

points on situations where a technique would or would not work well could be added to the technique summary paragraph. Having the ability to iterate scenarios was discussed and the workshop attendees suggested that having the ability to save an output file which could be edited and then used as an input would be beneficial to enable users to modify scenarios and review how inputs affected the selection process.

The workshop attendees were asked if coal and basalt should be included in the selectable storage options. The recommendation was to include these as monitoring case studies and to focus the scenarios on the storage options where confidence that they could offer giga-tonne scale storage was high. Monitoring coal and basalt storage focuses on geochemical interactions in the storage formation and potential leakage at surface and techniques for this are included in the MST.

The workshop attendees indicated that to be useful for an operator a tool either needs to offer broad and generic information that provides options, or something very specific to recommend a monitoring programme. The workshop attendees recommended that the MST should focus on providing a list of options for review, instead of a hugely detailed tool to make recommendations. Each operator will have their own processes and risk appetite for individual projects.

Maintaining the full TRL technique catalogue was discussed. The workshop attendees said it was useful to have techniques from the full range of TRL and recommended to keep expanding the techniques catalogue. It is important to be clear on tool maturity and where they have been tested/deployed. There has been a lot of progress in 20 years of monitoring towards a more streamlined approach. Commercial storage operators are focused on confidence in the site, not testing out every tool. It is useful to know what tools have been approved elsewhere through a storage licence, and the locations where techniques have been demonstrated. The MST output offers a list of techniques and users can down select to what is needed to meet project needs. The workshop attendees indicated that storage operators are interested in understanding what is needed to make lower TRL tools deployable at commercial level.

The possibility of making the MST more visual was discussed, for example by providing images of a typified storage site with the selected monitoring techniques imposed on the image. The workshop attendees felt a visual approach was a ‘nice to have’ since it would likely require a lot of work, and it wasn’t clear that the benefit would be proportionate.

Overall, the workshop attendees recommended considering who the MST is for, how they will use it, and who will benefit most to achieve the best results for the resources required in future updates.

9.3 SUMMARY OF WORKSHOP RECOMMENDED ACTIONS FOR PROPOSED FUTURE UPDATES

1) Keep it simple
2) MST should output options to inform decisions, not provide a decision
3) Consider collecting anonymised data or analytics on who is using the MST and which pages they use
4) Confirm who will benefit most from the MST, who will use it, what are their goals?
5) Need to encompass pressure footprint of storage
6) Add risks to the front page alongside monitoring aims
7) Consider jurisdiction and common themes from regulations to see how these can be included
8) Consider adding an input/output file function to allow for evolution of monitoring programme over time

9) Consider adding a couple of key points about the technique at the top in the technique catalogue
10) Remove coal from front page as storage type but add monitoring case studies and examples for coal and basalt
11) Ensure it is clear how selection/ranking is done, why technique not selected
12) Case studies to show where a tool has been demonstrated before, including as part of an approved storage licence is helpful. Update to add more
13) Maintain the full technology readiness level catalogue. Consider how it could communicate what is needed to make that tool deployable
14) Making the MST more visual is a nice to have, focus more on the technical content
15) Consider the complementarity of tools.

10 User survey results

Following on from the interviews (Section 8) and workshop (Section 9) a short survey was designed in order to reach a larger number of Monitoring Selection Tool users and potential users. The aim of the survey was to ask the monitoring community to rank the list of aspects that could be improved in a future update of the MST. The list of potential improvements was built using the recommendations from the interviews and workshop. The survey was sent out by IEAGHG to their newsletter mailing list, forwarded to various personal contacts, and shared via LinkedIn. The survey **Error! Reference source not found.**was opened 24th July 2024 received 36 responses over a period of two months.

The main aspect of the survey was to rank the following options for the update:

1. **Please rank the following options in order of priority** by dragging and dropping each option into position, highest priority at the top, lowest priority at the bottom:
    - **Make the Monitoring Selection Tool more risk-led rather than the current scenario-led approach** (i.e. focus on risks to capacity and containment such as legacy wells, induced seismicity, pressure, fluid migration, essentially changing the starting premise from ‘can we store here’ to ‘should we store here’)
    - **Expand the Tool Catalogue detail to cover deployment aspects** (e.g. add more headings/sections on maturity of tools, scales of site where deployed, use in storage licence applications, timeframe to show phases and frequency of application)
    - **Add more technical details about tools** (e.g. how the tool works, strengths and weaknesses, more detail on costs, more example case studies)
    - **Update the bibliography more often and add more links** to allow people to research tools more thoroughly
    - **Expand the justifications of how and why tools are identified as ‘core’ or not** e.g. including tool maturity/deployment experience, complementarity, practical considerations for access/deployment
    - **More flexibility in the storage scenarios** e.g. expand reservoir lithologies to basalts/coals/limestones, risk-led/adaptive monitoring (up- or down-selection of tools) to reflect changing needs during storage project lifecycle, enable enter number to define depth, more detail on wells/nearby operations
    - **Make the tool more visual** e.g. ability to output a schematic of the scenario, bow-tie approach to risk and mitigation, comparison graph of tool ranking

The survey respondents were also given the opportunity to say if they had used the MST previously or planned to use it in the future, how they used the MST and how long they had

worked in CCUS. Users were also offered free text boxes to comment on the ranking of priorities for future updates, and also at the end to add any additional context.

10.1 HOW RESPONDENTS USE THE MONITORING SELECTION TOOL

About a third of the respondents had previously used the MST (31%), the vast majority (95%) said they would or might use it in future.

Survey respondents reported they used the MST to review or 'sense check' monitoring options, as a checklist to help develop a monitoring plan, or as a teaching aid. Respondents indicated that in future as they would continue to use it for these purposes. Respondents also indicated that in future they would/might use the MST to review storage site Measurement Monitoring and Verification plans, to help clients and provide advice to stakeholders, and to help assess risks of each project and the impacts on their community.

10.2 USER COMMENTS AND SUGGESTIONS

A summary of the ranking of options indicates that making the MST more risk-led was strongly supported. This was closely followed by expanding the knowledge base technique catalogue to include more on deployment aspects such as maturity of the technique, scale of sites where deployed, use in storage licence applications and timeframe to show phases and frequency of application.

Updating the bibliography and adding more links for further research was ranked as the lowest priority by survey respondents.

10.2.1 Adopt a risk-led approach

Overall, making the MST more risk-led was ranked as the top priority by survey respondents (50% ranked it as their first priority, and a further 17% as their second priority). There were a couple of additional comments on focusing on risk and linking the monitoring techniques to managing that risk.

10.2.2 Expand the user input options

Comments recommended updating the scenario generator to provide an output that incorporated multiple monitoring phases simultaneously, as well as adding environmental and community outreach to the monitoring aims. One respondent observed that the land-use options don't really cover offshore uses. In-situ carbon mineralisation was recommended as an additional storage type. One respondent requested indicating the preferred state (e.g. dense phase, gas, or dissolved in fluid) for CO_2 injection and minimum depth based on different storage types.

One respondent asked for a costing aspect to be included. Another asked that project economic feasibility based on source-sink distance and storage depth be considered.

10.2.3 Add more case studies and information on where monitoring techniques have been applied

The addition of information from operating projects and storage sites in the advanced planning stage was recommended, including which monitoring techniques are included in their published Monitoring Measurement and Verification plans. An update to the costs was also recommended.

10.2.4 Provide additional details on monitoring techniques

Update and provide additional detail on maturity of tools, scales of site where deployed, use in storage licence applications and timeframe to show phases and frequency of application was also ranked as a high priority by survey respondents (19% ranked this as their first priority, and 22% as their second priority).

In their comments, respondents requested an update to the TRL for all technologies, a section on limitations of each tool, guidance on which techniques are most commonly used, and detail on deployment modes (permanent vs survey, and if new or existing wells could be used).

Overall, it was recommended that the technique catalogue and costs be updated to reflect the latest data available with a consistent approach to each entry.

10.2.5 Add new monitoring techniques

Respondents noted that fibre optic systems (DAS/DTS) and wireless downhole gauges for monitoring the storage formation and underburden are missing from the current MST version. One respondent recommended more on monitoring induced seismicity with passive and downhole techniques (the BGS team wish to note there is a section on microseismic monitoring but this could be expanded or made easier to link to induced seismicity).

10.2.6 Provide additional clarity on the selection and ranking of techniques

Some respondents found the rating system lacking in clarity. One respondent commented that if the MST becomes more risk-led, then this aspect of ranking techniques would become more important since the user would need to understand why a monitoring technique is associated with a particular risk.

10.2.7 Improve user experience

Survey respondents suggested that adding an overview and quick tutorial could be helpful. One also commented that they did not like using the colour red for the 'core' techniques. It was also recommended that the MST be made more user-friendly for students by including an inline description of each technique and a flowchart of CCUS.

10.2.8 Comments from a storage operator

One respondent identified themselves as a storage site operator and indicated that the MST was too generic for use at a real site past the screening stage. They did however say that the resources collected are very useful for new and experienced contributors, and they encouraged keeping the knowledge base up to date, including the bibliography.

11 Technical content considerations

11.1 GENERAL RECOMMENDATIONS FOR FUTURE UPDATE ON THE TECHNIQUE CATALOGUE

While undertaking the current update, the BGS team made a few general observations for the technical content for future updates of the Monitoring Selection Tool.

Over the next few years it is expected that many storage licences will be issued (for example, as of 17th March 2025 in the UK there is one storage permit and 26 additional appraisal and storage licences (NSTA, 2024), in Denmark there are six exploration licences awarded and four licences available for tender (Energistyrelsen, 2025), and in Norway there is one exploitation licence and 12 exploration licences (Sodir, 2025) plus Sleipner and Snohvit storage sites). Even basic information (e.g. amount of CO_2 injected) is not always easy to find. It may be necessary to consider how much information should be included and how to select which storage sites will be added.

The seismic techniques (currently nine catalogue entries) part of the catalogue may need to be restructured, and consideration should be given to how many catalogue entries are needed to best cover this topic. There have been changes in relative importance of these techniques and other technical developments since the MST was launched.

More detail is needed on deployment of techniques, including a photo or diagram for how the technique is deployed to aid understanding of what is required to deploy each technique.

Consider adding a deployment cost indicator. For example, if deployment requires a plane, ship or well this needs to be highlighted to avoid a distorted view on costs. For example, sensors can be cheap to run but if a well is required or needs to have specific properties for a tool to work (e.g. fibre glass casing for some ERT techniques) then this should be indicated. Cost descriptors should include a date when they were estimated.

Attending technology conferences would facilitate the addition of new low TRL techniques and applications, and techniques that could be adapted for CCS applications.

In the longer term, some techniques may be discarded. A decision needs to be made if these would still be included in the knowledge base even if they are not available for the selection aspect of the MST.

12 User experience (UX) considerations

The BGS team considered how a future update to the Monitoring Selection Tool could accommodate current UX industry practices.

The Monitoring Selection Tool and other webtools are popular because they can be used as a starting point to scope out monitoring options and/or provide confidence in initial decision making around monitoring CO_2 storage. The challenge is in ensuring the MST is, and is seen to be, relevant and well-maintained, useful, usable and trustworthy. A useful set of recommendations on developing web calculators is available from UX experts in the US (Nielsen Norman Group, 2024) and consideration is given here to how these recommendations could be applied to the MST, taking into account feedback provided from the user interviews (Section 8).

12.1 OPTIMISE MONITORING SELECTION TOOL FINDABILITY FOR SEARCH ENGINES

When looking for a webtool, users often start with a search engine and will open a webtool directly from the search results, even if they are unfamiliar with the hosting organisation. To improve findability and optimise for search engines, keywords such as “monitoring tool" “IEAGHG,” “monitoring CO_2” etc. should be included in the title or keywords of the webpage that hosts the MST.

12.2 ALLOW EASY ACCESS WITHOUT THE NEED TO REGISTER

Given the intended purpose of the MST and the early project stage at which it’s likely to be consulted, most current MST users chose to use it anonymously and the option to register has now been removed. Users also generally prefer not to receive follow-up communications which is another reason for reluctance to register online.

12.3 EMBED THE MONITORING SELECTION TOOL ON RELEVANT HOST WEBPAGES

It is generally preferable for webtools to be embedded on relevant host webpages, rather than via dedicated pages or pop ups, providing this is not at the expense of tools loading quickly and running smoothly. The embedded frame arrangement of the MST seems to be the most appropriate solution.

12.4 PROVIDE INSTANT USER GUIDANCE

Input clarifications should be in line with the relevant input field and rather than in an instruction block or below ‘Add more info’ pop-ups/error messages.

12.5 ACCOMMODATE VARIABLE USER INPUT

The amount of information that can be input to the MST will vary among users and between storage scenarios. It is good practice to only require inputs that are essential for the calculator, with other inputs optional. However, default values may influence the user or infer an assumption, so are best avoided. Dropdowns and sliders could be useful when less precision is needed.

12.6 ALLOW EASY COMPARISON OF RESULTS AS USERS CHANGE INPUT

It is generally better to present results live on a webtool. It should be easy to adjust individual inputs and re-calculate or restart without having to completely re-input information unless specifically wanted by the user. Users like to see how their inputs affect outputs so ideally results should change dynamically on the webpage as users change their inputs. During interviews, users indicated that they would like to 'play' with the MST to see how their inputs affected the outputs. Result comparisons are potentially useful for an iteration of storage scenarios and as the monitoring plan evolves.

Offering to send users the output by email is generally not welcomed but an option to export the output should be included to allow the users to review their scenario outcomes and then to easily iterate with different inputs when they return to the MST, as suggested during the user interviews.

12.7 PROVIDE TRANSPARENCY ON THE UNDERLYING MECHANISMS

Some users like to see the algorithms used to generate the outputs. During the interviews, users showed interest in how the selection/ranking aspect of the tool works and providing more information on this could enhance user understanding as to why certain techniques are highlighted as 'core'.

13 Recommendations for future updates to Monitoring Selection Tool

Recommended updates are presented here based on stakeholder feedback received during the project and BGS team observations.

Future more in-depth revisions are required since there are new techniques and case studies that need to be incorporated into the knowledge base and selection aspects of the Monitoring Selection Tool (MST). The feedback obtained during this phase indicated several aspects of the Monitoring Selection Tool are positively viewed and should be retained. Users were positive on the need for the MST which indicates it answers a monitoring community need for such a product. The MST was described as simple and easy to use, and it was emphasised by users that it should remain so. The users stated that the MST is valuable in providing an overview of monitoring options via the extensive catalogue of monitoring techniques covering all TRLs.

A significant amount of feedback has been provided via the focussed interviews (Section 8), workshop (Section 9) and online survey (Section 10). The workshop and online survey helped prioritise options for the future update. The priorities for future updates are as follows:

- Rewrite underlying code to support longevity
- Develop a risk-led approach to reflect current practices
- Undertake user interface (UI) enhancements to align with modern expectations
- Promote and improve findability of the MST
- Add new monitoring techniques & update selection tables

- Update structure and content of the tool catalogue for consistency, add new information on existing techniques
- Add new sites and case studies to include more information on tool deployment and successes to enhance decision support aspects
- Provide additional clarity on ranking of monitoring tools
- Undertake user experience (UX) enhancements to improve functionality (with user testing on UX, UI and technical aspects)
- Enable more user input to the technical content

Clear communication on risk and mitigation and explaining how maturity of understanding develops is key for supporting the rollout of CCS. Efforts should be made to keep the MST accessible for new users and those new to CO_2 storage.

13.1 REWRITE SUPPORTING CODE TO SUPPORT LONGEVITY

Access to PHP scripting skills is becoming increasingly restricted, increasing the risk that 'repair' is more difficult if the MST fails. The MST will need to be rewritten, for example in HTML/Java as part of a future update.

The technical design of the solution and development processes would follow best practice according to the recommendations of the BGS Technical Design Authority (TDA). The BGS TDA is in place to ensure that technology initiatives are well conceived, effectively planned and deliver value. Recommendations would include which language and technical platforms to use, how to develop in an agile, team-based solution to minimise risk and improve maintainability. In future updates, user intelligence can be taken into account. The Monitoring Selection Tool would also then benefit from ongoing BGS initiatives to develop a generic platform for decision support tools.

13.2 DEVELOP A RISK-LED APPROACH TO REFLECT CURRENT PRACTICES

A risk-led version of the MST should be developed.

This will require a substantial update to the MST and underlying calculations (e.g. data tables used during ranking). Further consultation with user groups is needed to ensure correct design. The role of the MST is to support decision-making, not to undertake the decision.

The recommendations from the current feedback generally supported the idea of highlighting typical or key risks and considering how monitoring could be used to identify that the risk had materialised i.e. these key risks should be linked to monitoring tools. The scenario output should consider the change in uncertainty of understanding of risks as projects develop during site characterisation, operation and monitoring, for the defined storage site and injection scenario. As a project progresses, it is expected that uncertainty will decrease.

A more risk-led approach will require a change in approach to the MST with the type of risk being addressed forming the top criteria, prior to definitions of site description and monitoring aims. Outputs will include the risk barriers (monitoring tools), and then the information about the monitoring techniques that have been identified. This will be balanced with maintaining the simplicity of the MST interface and ease of access to data.

As projects could operate for 25 – 30 years, updates to the monitoring programme are expected and new techniques will become commercial over this timescale. A risk-led approach will also incorporate an evolving monitoring programme, so that users can explore an evolving risk profile as credible risks are identified, mitigated, and the monitoring programme develops with increasing maturity of understanding.

Risk category headings will be defined by considering the key aims of a monitoring plan (capacity, containment assurance, performance optimisation), the process for storage licence application in the relevant jurisdictions, as well as feedback from the current project; e.g.

categories could include storage capacity; injectivity; pressure footprint and interactions; CO_2 containment; environmental and groundwater protection; legacy well assessment; well assessment; community engagement. Whilst keeping an updated detailed list of regulatory requirements would be considered out of scope, key regulatory requirements could be accommodated. It is recommended to consider jurisdiction and common themes from regulations to see how these can be accommodated in a more risk-led version of the MST.

During the current engagement exercise, users highlighted that the monitoring aims aspect should be simplified. This will need to be accommodated alongside changing the MST for a more risk-led approach. The monitoring aims highlighted by user feedback during this project included containment, assurance and performance objectives.

13.3 UNDERTAKE USER INTERFACE (UI) ENHANCEMENTS TO ALIGN WITH MODERN EXPECTATIONS

The user interface needs to be updated and simplified to align with modern expectations for webtools.

To make the user interface of the tool more engaging intuitive navigation is important. Making navigation straightforward with clear labels and easily accessible controls will contribute to this. Providing immediate and clear feedback for user actions (e.g., button clicks, form submissions) through animations, colour changes, or notifications would be expected to make the MST feel more responsive. The design needs to be accessible to all users, including those with disabilities by following guidelines such WCAG (Web Content Accessibility Guidelines).

The site parameters input page received feedback recommending both more detail and simplification. The data entry form should be updated (e.g. it is very easy to miss the boxes for entering injection amount).

The current monitoring tool visual design should be modernised. The MST should follow the IEAGHG brand identity which includes using a consistent colour scheme, typography and iconography. It is recommended to use minimalistic design and to declutter the space by using sliders, dropdowns and minimal infographics.

13.4 PROMOTE AND IMPROVE FINDABILITY OF THE MONITORING SELECTION TOOL

The feedback on the MST was overwhelmingly positive and users recommended promoting it to attract more users.

This could include marketing at CCS (e.g. GHGT and IEAGHG) events, and also events focused on monitoring (e.g. All Energy, Oceanology International). Presentations to IEAGHG members and dedicated webinars would also raise the profile and offer additional opportunities to obtain feedback to inform future updates. Promoting the use of the MST for training courses such as the IEAGHG Summer School, or CO_2GeoNet schools would also attract users that are new to the CCS sector.

The MST should also be optimised for findability with search engines by adding to the webpage that hosts the MST.

13.5 ADD NEW MONITORING TECHNIQUES

During the current project, users highlighted three new techniques that need to be added (optical fibre, wireless downhole gauges, wearable sensors with GPS adapted for monitoring).

Variations on existing technologies such as permanent seismic sources, sparse monitoring with seismics, passive seismic survey techniques, tracers also need to be added. Seismic techniques were highlighted as having significantly developed which might require a change in the number of entries or how they are grouped in the catalogue. Pressure has become a focus

in monitoring CO_2 storage sites and users highlighted that this didn't come across sufficiently in the current version of the MST.

Users were very keen to maintain the full catalogue of tools showing the range of TRL but recommended the tool be clearer when presenting low TRL techniques and explain deployment requirements so that the user can decide if they want to apply a technique for their project. Low TRL tools are of interest to researchers and pilot/testbed operators looking to develop new techniques and to see what is coming soon. Including lower TRL tools supports further innovation.

13.6 UPDATE STRUCTURE AND CONTENT OF THE TOOL CATALOGUE FOR CONSISTENCY, ADD NEW INFORMATION ON EXISTING TOOLS

It is recommended to update the technical content of the MST technique catalogue to provide a consistent overview, thus allowing users to compare techniques more easily.

This would include updating the structure of the tool descriptions to ensure consistency. Where possible practicalities of deployment, examples where the tools have been used (successfully and unsuccessfully), and cost information will also be updated (and ideally reviewed every three years). Users also asked that the bibliography was updated.

During the current update where information was already available in the MST, the summary section was expanded to provide a uniformly structured and succinct introduction with key insights into the tool including practicalities of deploying techniques, highlights and lowlights, maturity, costs and use examples. This exercise needs to be continued in future updates with new information.

13.7 ADD NEW SITES AND CASE STUDIES TO INCLUDE MORE INFORMATION ON TOOL DEPLOYMENT AND SUCCESSES TO ENHANCE DECISION SUPPORT ASPECTS

New sites and case studies should be added to the MST.

Commercial storage sites, pilot and testbeds should be reviewed to consider which should be added to the MST site catalogue. This will depend on data availability and if the sites add new understanding or case studies for monitoring techniques in the MST.

Users highlighted that knowing where techniques have been applied successfully and unsuccessfully is key to their decision making. Being able to see where a technique has been used and whether and why it worked well or not will support users in assessing if a recommended technique will work for their site. Users appreciated and recommended an update to the benchmark page that shows where techniques have been used since this assisted in decision making on which techniques to use. Users noted that overall, the case studies need an update. Users requested that monitoring case studies that incorporate basalt and coal should be added in the technique catalogue.

Highlighting sites with a storage permit and which tools were included (during the different storage phases) was particularly interesting to the users since this factor would give additional credence a particular monitoring technique.

13.8 PROVIDE ADDITIONAL CLARITY ON RANKING OF MONITORING TOOLS

It is recommended additional clarity be provided on the MST selection process

An output/input function should be added to enable repeat prioritisation as scenarios develop. Users were interested to have the opportunity to see how variable parameters including the injection rate, the depth of storage and the duration of storage will, or will not, produce variations in the output of the MST. Although being able to save the input was not considered essential, users highlighted the value of being able to export the outputs and then use that as

input so they can update and develop the scenario; this is useful to enable users to repeat the scenario as they learn more over time and maturity of understanding about a site grows.

The selection of tools based on their complementarity should be accommodated by highlighting the benefits of having a range of information sources or measured parameters for a given site. This will enable users to create a package of complementary tools that are more likely to meet their monitoring aims.

13.9 UNDERTAKE USER EXPERIENCE (UX) ENHANCEMENTS TO IMPROVE FUNCTIONALITY

Ensuring a streamlined and smooth user experience that meets expectations of modern webtools, and enhancing functionality in response to user feedback is recommended.

Each step should be clear to prevent errors where possible, and instructive messages should be provided when errors occur, along with easy recovery options. Ideally explanations should be provided live on the page without users having to click away from the main page. The MST should be fast and responsive, so there is a need to optimise loading times and reduce lag.

One of the options being considered by the BGS team is the possibility of having expert/non-expert modes for the tool that would include default parameters or example sites (similar to modelling software where you accept defaults unless you have more data). The aim of the non-expert mode should be to enable users to view the outputs and compare results with different input scenarios, by taking minimal steps. This idea requires further exploration and discussion since providing defaults can unintentionally introduce bias.

13.10 USER TESTING FOR TECHNICAL CONTENT, UI AND UX MODIFICATIONS

User testing is important to the UI and UX process to ensure that the tool meets user needs.

BGS UX team will sketch out potential solutions and perform usability tests to understand user needs and expectations. As the next version is built, feedback should be obtained from the different user groups to understand their views, including any new “pain points”/gaps. Feedback has already been obtained to help steer planned future updates and it would be beneficial to go back to the community and see if the updated version meets their needs and recommendations. During the current project, it appeared that the main user groups were taught university students and researchers (including research groups within project developer institutes). During future updates, the team should re-engage with target user communities (broadening the scope if necessary) to refine and reinforce the outcomes of the current user engagement. Webtool redesign is always an iterative process. User consultation would continue throughout the update process, and a mechanism for feedback and consultation should be put in place longer term.

13.11 ENABLE MORE USER INPUT TO THE TECHNICAL CONTENT

It is recommended to collect anonymised data or analytics on who is using the MST and which pages they use to inform future updates, and to make user input even easier.

It was suggested that tracking which tools and sections are most used could be help prioritise longer term updates of the tool. Understanding what users search for and if they find it could help improve the MST. The aim of this action would be to improve user engagement by making the tool feel more interactive.

The ability for users to report issues is available in the current MST version and is still required. This should also enable users to suggest additional techniques, case studies and references. Suggestions would need to be reviewed to ensure they aligned with the expected MST content and functionality. Thus, future support for this activity needs to be reviewed.

14 Exploring User Experience ideas for future updates

During the current project, the team explored and mocked up a few ‘quick fix’ User Experience (UX) options to illustrate some of the required changes.

14.1 CHANGES TO THE SCENARIO GENERATOR

Many users advised to follow a more risk-led approach for the tool. The ‘Monitoring aims’ could be changed to ‘Risk to mitigate’ with updated category headings. It is worth noting that updating the category headings will require updating the ranking process that sits behind the MST.

Some users requested additional reservoir types, while others requested that the tool focused on storage types that could offer giga-tonne scale storage. New options could be added to the ‘reservoir type’, ‘land use’ and ‘monitoring phase’.

Header login tabs have been removed in the current online version since the option to login has been removed.

A mock-up these changes is shown in Figure 2.

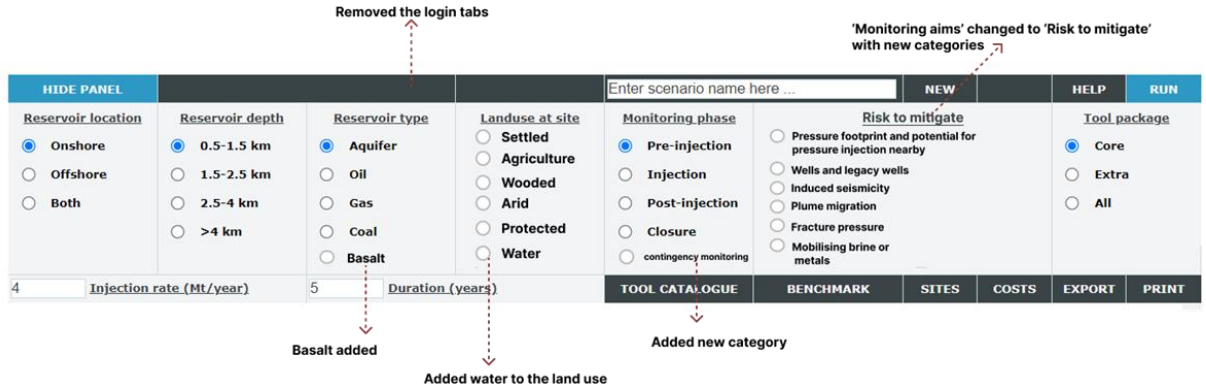


Figure 2 Scenario generator changes, modified from IEAGHG (2025)

14.2 ADDITIONAL DETAILS INSIDE THE CATALOGUE TOOL OVERVIEW

The overview should be further harmonised across the tool to provide additional details. For example, users asked for key insights to be added. This section should provide a succinct overview of each technique. Maturity of the technique, monitoring phase, scales/timing of deployment and use examples should be added to the overview.

This overview could be provided in a table, or additional sections could be added to the catalogue entry for each technique (mock-up in Figure 3).

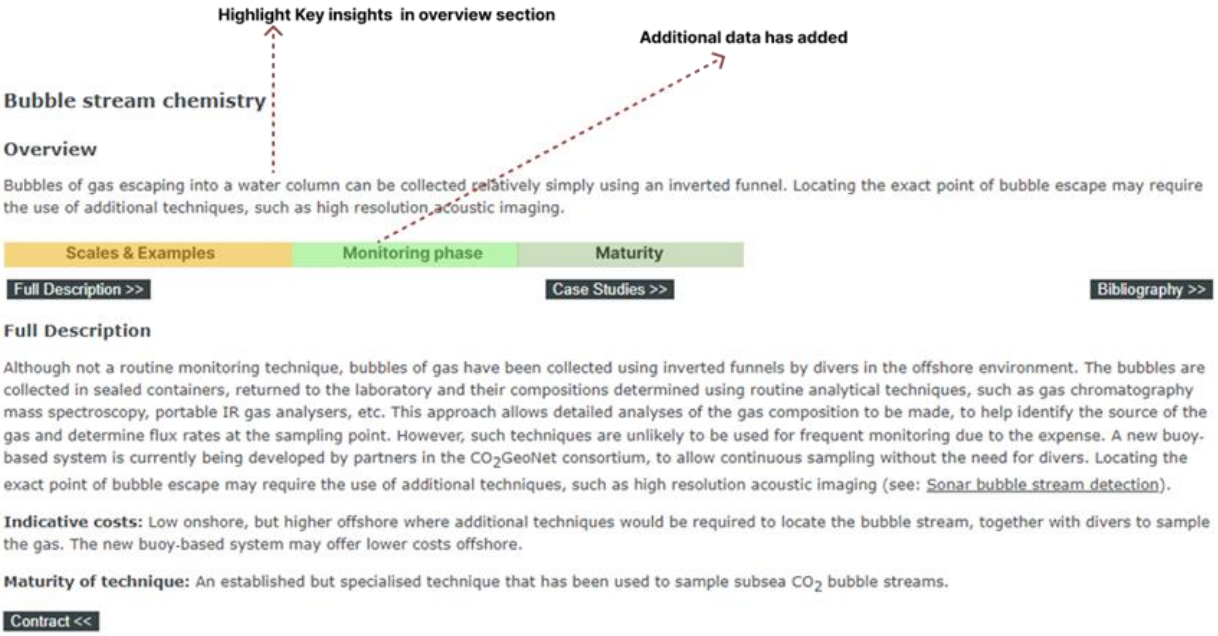
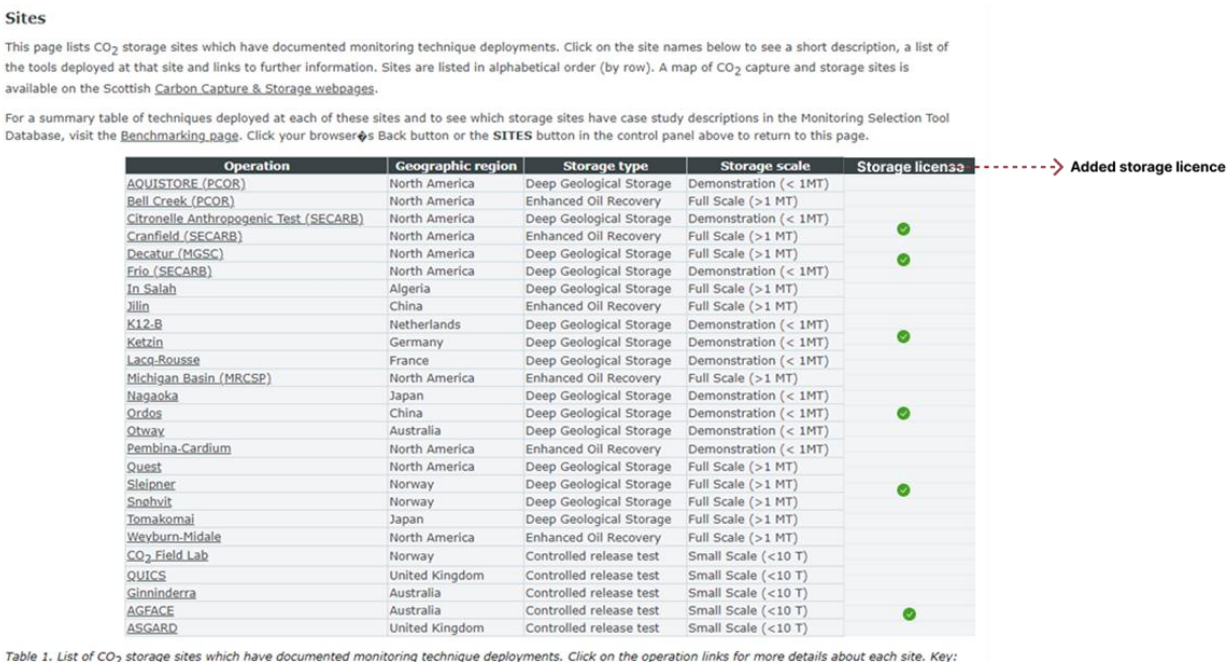


Figure 3 Additional details inside the tool, modified from IEAGHG (2025)

14.3 CHANGES TO THE STORAGE SITE PAGE

Users indicated that knowing which techniques had been used at existing sites that are operating under a storage licence would be beneficial since this gives additional confidence in the technique. One option considered as a ‘quick fix’ to make clear which sites are operating under a storage licence is mocked up in Figure 4.



Operation	Geographic region	Storage type	Storage scale	Storage licence
AQUISTORE (PCOR)	North America	Deep Geological Storage	Demonstration (< 1MT)	
Bell Creek (PCOR)	North America	Enhanced Oil Recovery	Full Scale (>1 MT)	
Citronelle Anthropogenic Test (SECARB)	North America	Deep Geological Storage	Demonstration (< 1MT)	
Cranfield (SECARB)	North America	Enhanced Oil Recovery	Full Scale (>1 MT)	✓
Decatur (MGSC)	North America	Deep Geological Storage	Full Scale (>1 MT)	✓
Frio (SECARB)	North America	Deep Geological Storage	Demonstration (< 1MT)	
In Salah	Algeria	Deep Geological Storage	Full Scale (>1 MT)	
Jilin	China	Enhanced Oil Recovery	Full Scale (>1 MT)	
K12-B	Netherlands	Deep Geological Storage	Demonstration (< 1MT)	
Ketzin	Germany	Deep Geological Storage	Demonstration (< 1MT)	✓
Lacq-Rousse	France	Deep Geological Storage	Demonstration (< 1MT)	
Michigan Basin (MRCSP)	North America	Enhanced Oil Recovery	Full Scale (>1 MT)	
Nagaoka	Japan	Deep Geological Storage	Demonstration (< 1MT)	
Ordos	China	Deep Geological Storage	Demonstration (< 1MT)	✓
Otway	Australia	Deep Geological Storage	Demonstration (< 1MT)	
Pembina-Cardium	North America	Enhanced Oil Recovery	Demonstration (< 1MT)	
Quest	North America	Deep Geological Storage	Full Scale (>1 MT)	
Sleipner	Norway	Deep Geological Storage	Full Scale (>1 MT)	✓
Snøhvit	Norway	Deep Geological Storage	Full Scale (>1 MT)	
Tomakomai	Japan	Deep Geological Storage	Full Scale (>1 MT)	
Weyburn-Midale	North America	Enhanced Oil Recovery	Full Scale (>1 MT)	
CO2 Field Lab	Norway	Controlled release test	Small Scale (<10 T)	
QUICS	United Kingdom	Controlled release test	Small Scale (<10 T)	
Ginninderra	Australia	Controlled release test	Small Scale (<10 T)	
AGFACE	Australia	Controlled release test	Small Scale (<10 T)	✓
ASGARD	United Kingdom	Controlled release test	Small Scale (<10 T)	

Figure 4 Changes to the site table, modified from IEAGHG (2025)

14.4 OUTPUT SCENARIO AND COMPARISON

Currently the Monitoring Selection Tool uses red, orange and violet for ‘core’, ‘additional’ and ‘potentially useful’ tools. Some users recommended that red should not be the colour for ‘core’ tools. Therefore, other colour schemes could be considered, for example in the mock-up in

Figure 5, the priority-based colour coding has changed to green, orange and grey. Accessibility requirements and guidelines will be referenced for future updates.

Users indicated that being able to quickly assess the relative maturity and costs of each technique could also be useful. Cost, Technology Readiness Level (TRL) and deployment scale columns could be added for quick reference. Users could then view other parameters in the comparison chart presented in the compare tool dropdown for more detailed information.

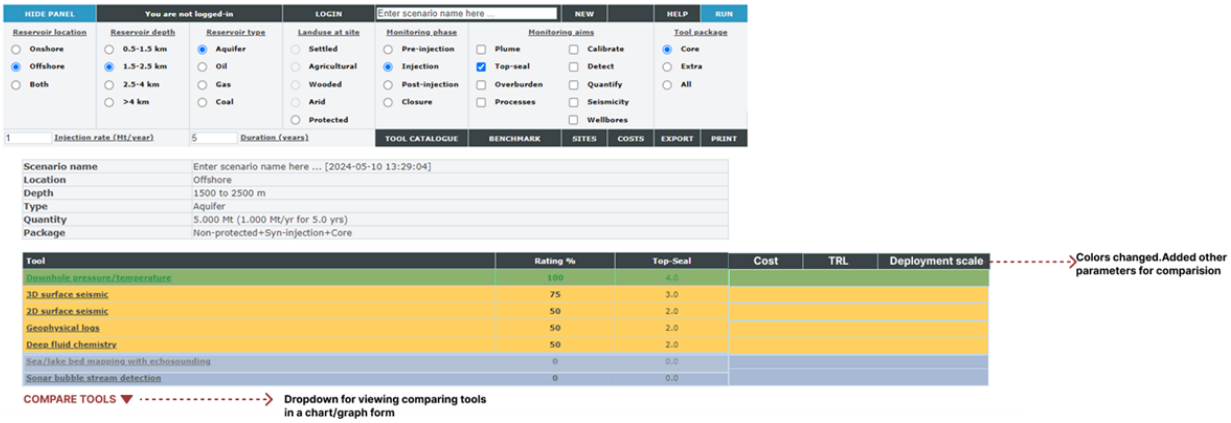


Figure 5 Output scenario, modified from IEAGHG (2025)

15 References

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A1 Appendix 1: Notes from user interviews

15.1 INTERVIEW QUESTIONS

The interviews were divided into two sections to assess the desired technical and user experience updates:

Technical content

- How and how often do you use the tool within projects?
- What are your expectations for the tool?
- Which aspects of the current tool do you use?
- Does the tool provide all info that you are looking for? Is there any additional info that you are looking at? Should anything be removed?
- Should tools from the complete Technology Readiness Level range be included, or should focus be on tools already used at full scale storage sites?
- Do you need more explanations for the terminologies used in the tool?
- Does the approach of the tool need to be modified (e.g. current version starts with storage site physical conditions and then monitoring aims)
- Any other comments on technical content?

User experience questions

- Did you have any difficulties while using the tool?
- When you are starting a new search, what are the main criteria you would use?
- Have you ever used a product similar to this one? What could we learn that might improve a future version of the monitoring tool?
- Do you need an option to save the current scenario that you are creating inside the tool?
- What sort of device (PC/laptop, mobile phone or tablet) would you expect to use when using the monitoring tool?

A summary of the comments from the different groups interviewed is provided below.

15.1.1 University students (views from the teaching staff)

Positives:

- Used quite a lot for teaching, provides backgrounds on all tools that could be used
- Useful to have full TRL range of tools
- Terminology is well explained
- Tool is simple and works well
- Tool is unique
- Tool is very useful and intuitive to understand and recommend suitable technologies for CO_2 monitoring

Recommendations:

- Should be more risk-led and linked to regulations. Start with a risk catalogue consider maturity of understanding of those risks. Monitoring tools should be specifically used to remediate risks.
- Provide a checklist – what are key risks and then link that to tools
- Be clear; EPA tell you what to do and give simple examples, this is a helpful approach
- There is now a strong emphasis on pressure for monitoring (including history matching), not sure this really comes across currently. Wells also need to play a larger role in a risk-led scenario
- Case studies need updating

- We have an online tool where you can export the outputs and then use that as input so you can update and develop the scenario; this could be useful here so that you can redo the scenario as you learn more over time and think about maturity of understanding of a site
- Make sure there is a way to report issues users experience

Other information

- For teaching we use example sites and work through development of a monitoring plan, debating what is the best answer
- Costs help you decide if you really need to use a particular tool
- USA regulations are focused on groundwater protection
- USA deal a lot with legacy wells

15.1.2 Research organisation

Positives:

- Provides a nice overview and list of tools to pick from
- Some tools are always core; a strength of the tool, shows the tools you have to use
- Good tool and easy to use. Provides all the information in one place, a good initiative

Recommendations:

- Useful to understand what other projects have used for new operators; what have other governments approved in terms of monitoring?
- Include more papers to show where tools have been applied. Would be nice to have a constantly updated reference list (e.g. weekly)
- Globally we are starting to have multiple approved storage permits and some are public domain. Extend the tool with more case studies of real projects and monitoring programmes
- Could maybe make some pre-set scenarios
- Regulatory aspects could be included
- More detail on the site would be beneficial; lithology, over- and under-burden, faulting and compartmentalisation
- Pressure and temperature are important and standard monitoring tools. Current reservoir pressure could be added to the site parameters
- The ranking offers tools that are suitable, would like to know more on why some tools are considered unsuitable/low ranking. For example, seismics are not particularly useful to quantify CO_2 in depleted gas field stores. Could the reasons why tools are ranked high/low be explained? Might make the tool more complicated
- Monitoring aims can change with time
- Monitoring Tool is currently hard to find online, could market it at relevant conferences
- Add more on costs
- Useful to be able to save and share output from Monitoring Tool

15.1.3 Research site operator

Positives:

- Good to see whole TRL range of tools. Might see something lower TRL we can improve or new tools that come along during the middle of a CCS project. May find unusual sites that require a previously non-commercial technology. Some tools are less well known and think Monitoring Tool offers an opportunity to think about how to use them
- Tool descriptions are useful
- We use the tool catalogue and benchmark

- References useful to see where commercial operators have applied a tool and ability to learn more and to confirm tools remain contemporary
- Idea behind the tool is good. The aims of the tool are clearly stated
- We point to the tool for education and coursework as an initial go-to for a range of technologies. And also for commercial work to consider how to monitor for various risks.
- Haven't seen any similar tool for monitoring technologies
- In my opinion this Monitoring Tool covers many tools. It is beneficial. Extremely useful to have a simple tool for selecting monitoring technologies. Monitoring Tool is good to get an overview of CCS monitoring

Recommendations:

- Aim of monitoring is usually containment, assurance, performance. Containment to check CO_2 is staying where it should. Assurance for local population. Performance and conformance look at how well utilise the resource especially if constrained. And reservoir response. Sometimes that gets lost. Think about who uses information; operators, regulators etc. maybe breaking information into those three monitoring aims and giving relative importance of tools for each aim
- Criteria are too restricted relative to where we're at in CCS these days. Want to include dimensions of site so you can think about how to monitor that and where. Should be risk targeted – containment etc. Think we're beyond thinking just about reservoir type. Interesting to see coal in there.
- Hard to see how to achieve risk targeted approach. Need to have ability to say risks are this and see which tools will apply. You do have monitoring aims, maybe if had fault leakage could tick that and then see what tools need to use
- Will you expand to include basalt?
- Monitoring aims checkbox provides too many options. We have monitoring aims are operation and CO_2 plume monitoring, and environmental monitoring
- Consider practicalities of applying tools – e.g. surface access or conditions, power requirements, permanent deployments, costs, area you need to cover etc so that users can make decisions.
- Do you consider how machine learning is being applied to various monitoring techniques? We used ML to try to predict next image of plume and it was scarily accurate
- Is the monitoring programme integrated with the national requirements for subsurface monitoring? E.g. if I could select the country where my site is located, will it provide a suite of MMV methods am I obliged to use by regulations? Does this relate to core and non-core?
- Like the low TRL since we develop technologies and try to commercialise. Maybe need TRL listed against each technique. Knowing e.g. 5-6 different projects have used a certain technology is an opportunity to get together and see how tool performs
- Like to apply the philosophy of finding combination of tools that have different strengths with respect to imaging over different ranges of pore space saturations – e.g. combine ERT with seismic. Consider complementarity of tools.
- Would be preferable if could suggest adding methods in the middle of the project
- When a tool is recommended, is there a way of judging if that will work for my site? People tend not to publish if a tool was unsuccessful but if you can find references that explain where and why tools were unsuccessfully applied this would be beneficial. Could you also provide a separate page of which tools are contraindicated – e.g. if the surface conditions are unsuitable
- Need to provide information on tools so that the user can make decisions (e.g. cost, technical maturity). Also consider tools that are being adapted (e.g. wearable detectors with GPS). Pre-commercial systems should be identified and maybe recommended separately to the systems that are tested in the environment of deployment

- Providing a short explanation is better than a long explanation; provide a short explanation first with a picture, then we can look at the detail if we want to
- Update the list of references, some key ones are missing e.g. on tracers, mixing model in air
- Please update the case studies, our site is shown as having injected less CO_2 than we have
- Seismics have developed, tool doesn't do this justice
- Important to maintain and update relevant costs more than the ranking in the Monitoring Tool
- Would be nice to have quick descriptions to access from the field
- Would like to fully understand why the tool may have been selected, maybe that could be handled with a keyword approach where there were particular keywords that must come up. Like table with list of references?
- Would like to have the opportunity to see how variable parameters, the injection rate, the depth of storage and the duration of storage will, or will not, produce variations in the response sent back by the tool.
- Do you capture the results of people's searches and which references they go to? Could you use machine learning to understand how different users search and use the information? Could help you understand which aspects of the tool to focus on. Could you consider asking which sector they work in?
- Let users recommend additional references and their keywords that the managers of the Monitoring Tool will consider adding to the system. If those searches actually generated a serial number, then this could help check if a paper didn't come up when users searched, or if the paper needs to be added
- Colour of rankings is not great
- Good to get this Monitoring Tool known more widely

Other information

- Some tools are so standard like wireline logging, that commercial companies might not even think of these as monitoring, they are just business as usual. And yet these might be the most useful
- Great to have downhole gauges so that you can directly monitor pressure and phase of CO_2 for sites near phase transitions
- Regulators may have unrealistic expectations of what monitoring can do so bringing them into process and along for the ride could be informative

15.1.4 Project developer/operator (including research teams)

Positives:

- Lovely to have benchmark – nice to understand where tools have been used
- Like the examples and references and case studies a lot
- Tool could be a useful starting point for new operators to become aware of what they don't know – too generic for the detailed risk assessments we use for sites (but don't suggest you make the tool more detailed since operators all have own processes)
- Having the whole TRL spectrum is good. With a long research history in research, we know tried & tested tools and a good idea of what we're using, but as researchers having guidance on newer tools is useful from our perspective

Recommendations:

- Needs to be more risk-led, your approach is more environment led. Think about what might go wrong/break and what you need to look for to identify the problem – e.g. brine or CO_2 getting into drinking water. There are some aspects of issues but not much currently – consider e.g. legacy wells

- Would like to see e.g. you follow the threat branches of the risk bow tie and when you click on the barriers (e.g. 3D seismic) you get the information about that tool. Something a bit more visual.
- We start with bowtie with all credible risks. Bowtie workshop and that establishes the premise for our monitoring programme. Think about why you are monitoring. Then think about technologies we have from years of experience. As learn more about site, update bowtie, branches disappear and only those threats that are credible remain. Bowtie is more of a communication tool. The work done in the background is by a team, not an individual
- Cookbook of techniques, but need to understand how to apply
- Post some key insights at the front. Could elevate some key insights and learnings that pop up right away (e.g. issues with seismic monitoring of depleted gas fields)
- For the tool explanations have a few lines and show a paper on where it was used
- Evolution in monitoring plans should be reflected as risk profile changes, including down-selection. We started with more tools and are removing tools we've seen are not cost effective/efficient. Here is could be useful to save the scenario. If you see issues add more monitoring, if site is behaving above expectations might drop some tools.
- Saving the output is not essential but would be nice if you are just making small adjustments
- Benchmark of sites is nice but make scale at which it has been applied, success rate, and how often have to repeat easier to understand.
- Researchers have a different approach, suspect people in operations won't use the Monitoring Selection Tool since they know their site. But for developing suites of technologies to inform decisions those people are making this tool is useful. Having an up-to-date repository - very helpful for us to keep eye in and know what's coming up.
- Show where tool was used successfully – offer entrance to rabbit hole so users can learn more and explore that technique, add more references
- Build on user cases studies more
- Add applicability, rate of success of tool. How frequently a tool is used. A huge component in deciding to use. Benchmark shows where but not how often have to use tool
- Suggest link to STEMM-CCS environmental monitoring tool
- Pressure and using this to monitor - e.g. pressure pulses between monitoring wells to test compressibility to see if there's been a leak; great to make you think about technique; how does it work? how could we make it work?
- Consider wellbores and accessibility, how you approach the questions.
- Would be good to have suites and understand complementary tools so you are not relying on one type of data
- Expectations for the tool: Almost worth coming up with a list of questions about how might use benchmark and how might use what's there
- Who is the target audience? People new to CCS or practitioners who want to find more information?
- Expecting primary audience would be CCS developers
- Looking at storage options - not sure would store that deep
- A section on fibre optic tools and lower TRL options should be included with limitations clearly stated. Fibre optics – not yet 100% end to end solution. How to analyse data in real time a challenge – we do it but not 100% efficient and we need more automation to get full value. But this shouldn't stop us from deploying fibres now when we have projects that will run 25-30 years. Not all done and dusted yet for fibre optics. Produces terabytes of data, this is why we need ML and processing in real time. Also, more on how to integrate with other tools

Other information

- We ask for each site; should we store? can we monitor efficiently this store? Cost pressure drives efficiency
- We are focused on tools applied at full scale
- Won't use a technology unless it helps diagnose a problem
- Do you see simple tried and tested tools at commercial sites, and out-there tools at the smaller sites?
- We have an internal benchmarking toolkit being built out for projects and it includes monitoring. We are pulling together material for this. Interesting how it has evolved. More around a list rather than a hierarchy sitting behind that tool e.g. monitoring wells – above reservoir? In reservoir? What do we put in those wells? Do people use those wells differently? A few different ways of cross-referencing the data depending on approach. Maybe want to know everything about the top 50 m/biosphere? Or might say it's all about in-zone because can't use seismic.
- Individual threat branches in the bowtie are independent. Leakage path might be a combination of multiple branches have to communicate this to get the message across. Migration across caprock and into overlaying layers and into abandoned well for example. Monitoring technologies that are relevant for a particular risk are then selected. Bowtie useful approach
- Interesting to think about sites with and without closures. Column height of CO_2 plume lower for migration assisted storage so less build-up of pressure on seal
- Would like more time to test how sensitive the output is to small change; what happens if I tweak parameters a bit, is the output a product of the way the system is set up or a real sensitivity?
- Got some new results on microseismic using fibre optics, our site could provide a benchmark for that
- There are only a few companies who do CCS now. And that has to change to meet the global deployment that's needed. One of concerns we have – and why we go to conferences – most organisations don't know what they don't know.

A2 Appendix 2: Notes from IEAGHG Monitoring Network Steering Committee workshop

The Steering Committee were then asked to provide their insights on selected aspects.

What are the most pertinent parameters to rank the monitoring tools? *The tool produces recommendations for 'core', 'optional' and 'all' tools that could be applied*

Discussion:

Area of review or area where pressure is elevated is not well expressed in the tool at the moment. This is particularly important for onshore and protection of groundwater resources where need to consider if displaced fluids could affect groundwater.

From the interview feedback there was a comment that the tool could consider layers in overburden more, for example secondary seals and aquifers, and how these could be monitored.

Initial feedback has suggested the tool should be more 'risk-led'. In practical terms, how would you adjust the front end of the tool to make it more risk-led? *Tool is currently scenario-led, i.e. you select the physical parameters of the reservoir and monitoring aims.*

Discussion

Need to use the word risk. This is additional to the monitoring aims that are already present in the tool.

Jurisdiction is very important in USA - onshore, offshore also. Groundwater protection is where CCS regulations started in the USA. Is it possible to consider common regulatory drivers? Keep the tool simple, allow people to focus on risks identified in their jurisdictions.

The IEA have a database of all regulations (IEAGHG, 2022)

How could we best represent selection of an evolving suite of tools over time – encompassing complementarity of tools, down selection during monitoring, and the overall timeline (storage project lifecycle) for monitoring operations etc. How would you adjust the front end of the tool to accommodate this? *Monitoring programme is not static or standard. Tools may be substituted with others e.g. if access to the surface is restricted, over time as some tools as some risks reduce with improved understanding, or where more cost-effective tools are identified*

Discussion

Including a timeline tool with different programmes is too complicated – keep the tool simple. Down selection is not a simple exercise and requires application of human expertise.

Need to really consider who the tool is for and how they will use it. Who will benefit most and how to achieve the best result for the resources expended. Key target audience and their goals is extremely important.

Operators have a list of questions from the regulator to answer. To be useful for an operator, either need something broad and generic that provides options or something very specific to recommend a programme. The tool should focus on providing a list of options for review, instead of a hugely detailed tool to make recommendations. Each operator will have their own processes and risk appetite for individual projects.

Storage operators are also interested to see what needs to happen to make lower TRL tools deployable.

Consider having a file that you output from the tool, and then can adjust and input back to the tool to update to enable iteration of scenarios.

From the interviews there was the recommendation to ensure there is enough information to understand how ranking is done and why a tool is not selected. And maybe add a few key points at the top e.g. at the moment can't distinguish between gas and CO_2 on seismic data.

Should coal and basalt storage be included in the selectable scenario options?

Discussion

Include as monitoring case studies – individually or combined - rather than storage options. At the moment we don't have the science to show these offer Gt-scale storage or for upscaling.

Monitoring these sites focuses on geochemical interactions in the reservoir and potential leakage at surface.

How much weight would you give to tools that have been deployed at licenced/commercial storage sites? Ie, should we focus the MST more on techniques that have been used at sites with a storage licence? Or maintain a comprehensive list of options?

Discussion

Useful to have the full range of technology readiness levels. Keep the tools in and keep expanding. Be clear on how developed tools are and where they have been tested.

Have made a lot of progress in 20 years of monitoring. From trying to get all the tools deployed to a more streamlined approach. Commercial projects don't want to be in experimental mode trying lots of tools. Fewer tools is an indicator of maturity of the CCS industry.

Monitoring programme at commercial sites is about confidence in the site, not researching tools.

We are still in the early stages of CCS commercial deployment though so our monitoring programmes will be different to when we have hundreds of projects operating.

Useful to know what tools have been approved elsewhere and where tools have been demonstrated before. What works and what doesn't is useful from an operator perspective.

Monitoring tool output offers tool list and will down select to what is critical to meet project needs.

Should the tool be made more visual – e.g. produce a picture output with the monitoring programme

Discussion

A nice to have. Sounds like will take a lot of work so how useful will this be to users? When have understanding of who will use the tool the most in the future, can decide if this is needed.

Focus more on technical content.

Can we collect data on who is using the tool and what they are interested in?

Discussion

Who uses and what the tools is used for are key questions. Could consider anonymised data (optional to provide) like having a tick box if they are an operator, student etc.

There are various 3rd party applications that could offer this depending on what we want to know

Summary of recommended actions for proposed future updates

1. Keep it simple
2. Tool should output options to inform decisions, not provide a decision
3. Consider collecting anonymised data or analytics on who is using the tool and which pages they use
4. Confirm who will benefit most from the tool, who will use it, what are their goals?
5. Need to encompass pressure footprint of storage
6. Add risks to the front page alongside monitoring aims. Consider jurisdiction and common themes from regulations to see how these can be included.
7. Consider adding an input/output file function so users can save the output on their PC and use that as input to allow for evolution/iteration of monitoring programme/scenario
8. Consider adding a couple of key points about the technique at the top in the tool catalogue
9. Remove coal from front page as storage type but add monitoring case studies and examples for coal and basalt
10. Ensure it is clear how ranking is done, why tool not selected.
11. Case studies to show where a tool has been demonstrated before, including as part of an approved storage licence is helpful. Update to add more.
12. Maintain the full technology readiness level catalogue. Consider how could communicate what is needed to make that tool deployable
13. Making the tool more visual is a nice to have, focus more on the technical content

A3 Appendix 3: Notes from online survey results

The survey was sent out by IEAGHG to their newsletter mailing list (Figure 2), forwarded to various personal contacts, and shared via LinkedIn. The survey (Figure 3) was opened 24th July 2024 received 36 responses between when it opened and 18th September 2024. The survey has been left open to receive any further comments.

IEAGHG Monitoring Selection Tool

Invitation to help shape development

IEAGHG are working with the British Geological Survey to scope potential future updates to the IEAGHG Monitoring Selection Tool, to incorporate operational experience from the rapidly-growing portfolio of CO2 storage projects worldwide.

We are inviting the CO2 storage monitoring community of current and future Monitoring Tool users to help shape its development by feeding your top priorities into a short survey:

Take Part In Our Quick Survey

For the live version of the tool, please select the 'Start tool without logging in' option click here:

Explore the Monitoring Selection Tool

The IEAGHG/BGS project team will use your contributions to produce recommendations for future updates to the Tool. This short survey should take only a few minutes to complete, and we really need your help to make the next version of the Tool even better!

Thank you for your support!

Figure 6 Invitation to provide input via the online survey from IEAGHG (by email)

15.2 SURVEY QUESTIONS

This section gives the key insights into features that users have prioritised the most. Respondents are asked to rank potential improvements, like updating the bibliography, expanding catalogue details, enhancing risk-focus, and making the tool more visual:

1. **Please rank the following options in order of priority** by dragging and dropping each option into position, highest priority at the top, lowest priority at the bottom:
   - **Make the Monitoring Selection Tool more risk-led rather than the current scenario-led approach** (i.e. focus on risks to capacity and containment such as legacy wells, induced seismicity, pressure, fluid migration, essentially changing the starting premise from 'can we store here' to 'should we store here')
   - **Expand the Tool Catalogue detail to cover deployment aspects** (e.g. add more headings/sections on maturity of tools, scales of site where deployed, use in storage licence applications, timeframe to show phases and frequency of application)
   - **Add more technical details about tools** (e.g. how the tool works, strengths and weaknesses, more detail on costs, more example case studies)
   - **Update the bibliography more often and add more links** to allow people to research tools more thoroughly
   - **Expand the justifications of how and why tools are identified as 'core' or not** e.g. including tool maturity/deployment experience, complementarity, practical considerations for access/deployment
   - **More flexibility in the storage scenarios** e.g. expand reservoir lithologies to basalts/coals/limestones, risk-led/adaptive monitoring (up- or down-selection of tools) to reflect changing needs during storage project lifecycle, enable enter number to define depth, more detail on wells/nearby operations
   - **Make the tool more visual** e.g. ability to output a schematic of the scenario, bow-tie approach to risk and mitigation, comparison graph of tool ranking
2. **Please feel free to add any further comments, suggestions or observations about the prioritisation or the tool here** e.g. user experience improvements, add/remove a feature or functionality

Users were also asked to provide some general demographic information for context. The survey was intentionally anonymous and users were asked not to include any information from which they could be identified:

3. **How long have you worked in CCUS?** (select from 0-5 years; 6 – 10 years; 11+ years; I am hoping to work in CCUS in future)
4. **Do you currently use the Monitoring Selection Tool?** (select yes/no)
5. **If yes at Q4, how do you currently use the Monitoring Selection Tool?** e.g. as a teaching aid for undergraduates/post-graduates, to review/sense check monitoring tool options, to develop a monitoring plan
6. **Do you expect to use the Monitoring Selection Tool in the future?** (select from yes/maybe.no)
7. **If Yes or Maybe at Q6, how might you use the Monitoring Selection Tool in the future?** e.g. as a teaching aid for undergraduates/post-graduates, to review/sense check monitoring tool options, to develop a monitoring plan
8. **Would you recommend the Monitoring Selection Tool to someone else?** (select from yes/no/maybe)
9. **Please feel free to add any further contextual information or comments here** e.g. if you wish to clarify a response or provide further information. Please do not include any personal information.

15.3 SURVEY FEEDBACK

A summary of the ranking of options indicates that making the Monitoring Selection Tool more risk-led was strongly supported (Figure 4). This was closely followed by expanding the tool catalogue to include more on deployment aspects such as maturity of the technique and maturity of tools, scales of site where deployed, use in storage licence applications, timeframe

to show phases and frequency of application. Updating the bibliography and adding more links for further research was ranked the lowest.

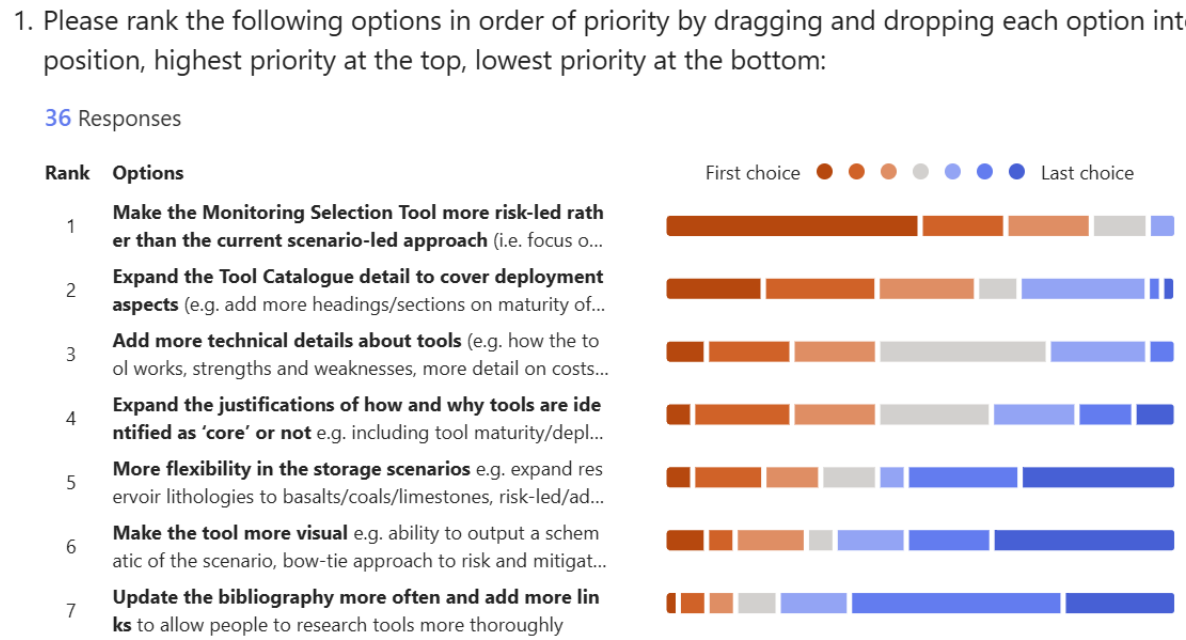

Figure 7 Results of the ranking question

A summary of the primary themes and specific user suggestions for improving the Monitoring Selection Tool based on the survey respondents' comments is provided below:

Enhanced Risk and Justification Framework:

- Multiple users suggested making the tool more risk-focused and framing around typical risks with features to evaluate and justify each monitoring technology based on specific site risks.
- A risk-led option could help users identify relevant monitoring technologies tailored to particular site challenges, and some mentioned the value of providing a justification for each tool's risk score.

Technical Information and Tool Maturity:

- Respondents requested more detailed technical descriptions, including technology readiness levels (TRL) and limitations of each monitoring method. This information could assist in selecting tools by understanding their maturity and applicability to various project phases

Addition of New Monitoring Technologies:

- Several new technologies were recommended for inclusion, such as:
    - Fibre optic systems (e.g., DAS/DTS for monitoring),
    - Wireless downhole gauges (for reservoir and overburden monitoring),
    - Passive seismic monitoring (surface seismometers, downhole geophones) for induced seismicity. Discuss sensor types/options (broadband seismometers, geophones, nodes/arrays, DAS. [please note passive seismic monitoring is currently included under microseismic monitoring]
- These technologies address monitoring needs not currently supported or highlight the need for clarifications

User Interface and Navigation Improvements:

- Users found some aspects of the tool confusing, such as the colour coding (e.g., red used for optimal tools) and the percentage-based rating system.
- Suggestions included revising the introductory page for a clearer overview and a more consistent catalogue structure to ensure descriptions, rankings, deployment, handling of different domains (e.g. 2D/3D seismic vs shallow pinger/boomer techniques) and categories are uniformly understandable.

Additional Context and Costing:

- Respondents highlighted the importance of providing cost estimates, including differentiation between deployment options (e.g., permanent vs. campaign-based monitoring).
- Additional economic factors, like feasibility based on source-sink distance and depth, and environmental factors, such as land use for offshore projects, were suggested to be included.

Feature Requests:

- Specific requests included adding environmental monitoring options, updating the sites in Benchmarking to include operating projects, updating the bibliography, and ensuring tool descriptions cover recent technological advancements and project examples.
- Some users requested a matrix feature showing where each tool has been used or is planned vs existing or proposed MMV plans published world-wide which would provide practical context and applicability across projects.
- The ability to choose more than one monitoring phase was requested to consider which monitoring technologies are applicable/relevant at the different phases of a CO_2 storage project
- Offshore 'land use' options were highlighted as missing

Functionality and User Feedback Mechanism:

- Some respondents noted that links to suggest new technologies were broken, which limited their ability to contribute updates.
- One user mentioned the lack of industry use cases to evaluate the tool's practical impact.

Environmental monitoring and community outreach:

- Some respondents noted to include environmental monitoring as part of the section of monitoring aims.
- Users suggested to use community outreach in the monitoring process.

These insights reflect a strong interest in expanding the tool's technical, economic, and risk-based capabilities, with an emphasis on user-friendliness and updated information

15.4 TOOL USAGE PATTERNS

This section explains how users currently use the tool or plan to use it in the future.

Most respondents were either new to CCS (0 – 5 years' experience) or well established (11+ years' experience) (Figure 8).

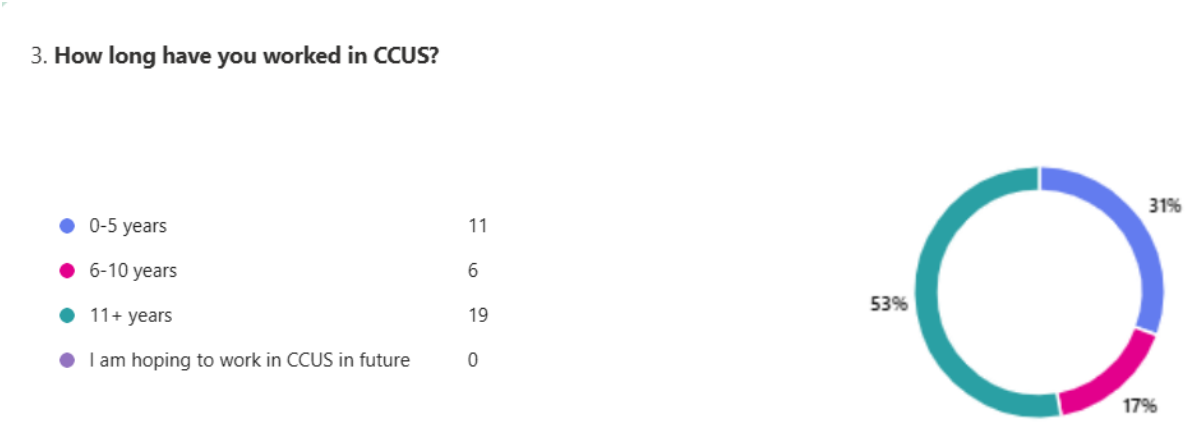

Figure 8 Response to question on how long users had worked in CCS

15.4.1 Current usage

- **Developing Monitoring Plans**: The tool is widely used to create detailed monitoring plans for CO_2 storage projects.
- **Teaching and Learning**: It serves as a valuable teaching aid for students and professionals in the field.
- **Reviewing Monitoring Options**: Users employ the tool to review and validate various monitoring technologies.
- **Strategic Purposes**: Some users use it for strategic planning and developing new monitoring strategies.

15.4.2 Future usage

- **Continued Use**: Users plan to keep using the tool for developing and refining monitoring plans.
- **New Applications**: There is interest in using the tool for new purposes, such as evaluating individual project proposals and developing new monitoring strategies.

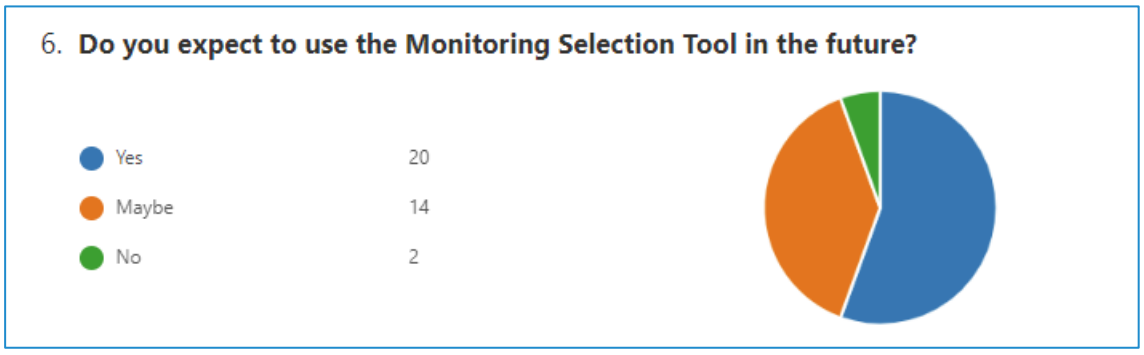

Figure 9 Expected future use of the tool by respondents

A4 Appendix 3: Future updates; general comments

Following the input from the survey, interviews and the IEAGHG Monitoring Network Steering Committee, a few general recommendations were summarised.

Some requests could be relatively easily actioned (e.g. updating the ranking colour scheme) and others will likely require a fundamental change to the MST structure and underlying architecture (e.g. making the tool risk-led, which in turn will affect the selection/ranking process). It is also worth noting that some feedback requests mutually exclusive changes (e.g. recommendation to include basalt and coal vs the recommendation to focus on monitoring for giga-tonne scale storage options). Some feedback could also be considered to lie outside the scope of the tool (e.g. including costs for source-sink distance in the ranking). Some of the recommendations could also potentially make the tool more complicated to use (e.g. including monitoring phases) and given that the simplicity of the tool was highlighted positively by several users, how, or even whether, recommendations such as this could be accommodated requires consideration. Some recommendations would also potentially be resource intensive (e.g. updating the bibliography every week). It is clear that not all recommendations can realistically be implemented and a means of prioritising options, e.g. on value to users vs complexity/cost of implementation, will be needed.

In future updates, further consultations should be undertaken to refine user needs to ensure that any user groups not already surveyed have the opportunity to provide feedback. Future updates should also account for learnings from the projects that will, by then, be permitted or operating. In the interval since the MST was first built in 2005 – 2006, the approach to monitoring CO_2 storage sites has evolved. The current light touch review has identified the continued need in the CCS monitoring community for the MST but has also highlighted the need to add new techniques, and to consider the priorities identified by new and upcoming projects. For example, in the CCS community project pressure footprint and pressure interactions between projects have become a key focus over the past few years as multiple projects move towards deployment and consider what this will mean in terms of density of projects. The focus around deployability of tools was also highlighted by storage pilot/testbed and operators during this current update, which is likely a result of more practical experience gained by users.

One of the technical changes suggested was a more risk-led approach. One option suggested could be to add risks to the front page alongside monitoring aims. If this does not answer the required need then it is likely that a more fundamental redesign of the approach of the tool is needed. This theme of risk-led would need to be supported by further consultation with identified and potential user groups to understand their objectives and expectations, needs and current working practices, and how the tool might be redesigned to accommodate these. The role of the MST is to support decision-making, not to undertake the decision.

Users suggested expanding the technique summary section to provide a uniformly structured and succinct introduction with key insights into the tool including highlights and lowlights, maturity/TRL, costs and use examples. Users also asked that any practicalities of deploying techniques were highlighted – e.g. surface access or limiting conditions, power requirements, costs, coverage area, legacy vs new well deployment, permanent vs survey techniques etc so that users can make decisions for their site.

Users were very keen to maintain the full catalogue of tools showing the range of TRL but recommended the tool be clearer when presenting low TRL techniques and explain deployment requirements so that the user can decide if they want to apply a technique for their project. Low TRL tools are of interest to researchers and pilot/testbed operators looking to develop new techniques and to see what is coming soon. Including lower TRL tools supports further innovation.

Costs are a key driver in selecting monitoring technologies and need to be updated regularly (i.e. every few years).

Users highlighted three new techniques that need to be added (optical fibre, wireless downhole gauges, wearable sensors with GPS adapted for monitoring). Variations on existing technologies such as permanent seismic sources, sparse monitoring with seismics, passive seismic survey techniques, tracers also need to be added. Seismic techniques were highlighted as having significantly developed which might require a change in the number of entries or how they are grouped in the catalogue.

Pressure has become a focus in monitoring CO_2 storage sites and users highlighted that this didn't come across sufficiently in the current version of the MST.

Users highlighted that knowing where techniques have been applied successfully and unsuccessfully is key to their decision making. Being able to see where a technique has been used and whether and why it worked well or not will support users in assessing if a recommended technique will work for their site. Highlighting sites with a storage permit and which tools were part of that licence (during the different storage phases) was particularly interesting to the users since this factor would give additional credence to selection of the tool. Users appreciated and recommended an update to the benchmark page that shows where techniques have been used since this assisted in decision making on which techniques to use. Users noted that overall, the case studies and bibliography need an update.

The main recommendations for future updates are as follows:

- Reconfirm user groups and their aims and expectations for the tool
- Maintain simplicity and ease of use
- Maintain the tool catalogue across the full range of Technology Readiness Levels
- Change the tool to have a more risk-led approach
- Accommodate learnings from new sites, regulations and particularly from issued storage permits
- Update the summary section for each technique to provide the key aspects in decision making for users
- Provide more transparency around how the Monitoring Selection Tool ranks techniques including, if feasible, why techniques are not recommended
- Modernise UX and UI aspects for a clean, streamlined user experience
- Re-write the code to a more commonly used language
- Track how the tool is used and ensure that users can easily provide feedback and new techniques or case studies
- Promote the tool and optimise findability
- Enable users to save their results

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