BRITISH GEOLOGICAL SURVEY

A scoping study for a deep geological carbon dioxide storage research facility

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Foreword

This report is the published product of a scoping study by the British Geological Survey (BGS) for a UK deep geological carbon dioxide (CO_2) storage research facility.

This study was funded through the UK Research and Innovation (UKRI) Infrastructure Fund and Natural Environment Research Council (NERC) Capital programme. The CO_2 storage scoping study was announced in the UKRI Innovation Strategy as part of the first £50 million portfolio of investments. Further details on the UKRI Infrastructure Fund can be found at https://www.ukri.org/our-work/creating-world-class-research-and-innovation-infrastructure/

The BGS scoping study was led by:

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- Rachel Dearden: permitting and planning
- Hazel Napier: development of social science, arts and humanities research questions that a facility might enable

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The invaluable input of the external expert steering committee is gratefully acknowledged, in particular, their time, effort and expertise in shaping the science questions that benefit UK carbon capture, utilisation and storage (CCUS) projects and research, and imparting their knowledge on technical and costing matters.

We particularly recognise leadership by Clare Bond of the University of Aberdeen, as chair of the steering committee, well expert Martin Koster and the committee members from:

- the universities of Bristol, Edinburgh and Sheffield, and Imperial College London
- National Oceanographic Centre
- Centre for Environment Fisheries and Aquaculture Science
- Shell
- UK Government Department for Business, Energy & Industrial Strategy (BEIS)
- Engineering and Physical Sciences Research Council (EPSRC)
- Arts and Humanities Research Council (AHRC)
- Economic and Social Research Council (ESRC)

The contributions from the CO_2 storage industry, regulatory and research stakeholders from the UK and Europe, and pilot and research sites around the world, were essential to the development of a robust science case for a deep borehole facility. Our thanks and full appreciation go to them for their interview, written and workshop contributions, which were freely given.

Summary

BGS presented a concept for a deep geological carbon dioxide (CO_2) storage research facility to the UKRI Infrastructure Fund Announcement of Opportunity in 2020. NERC prioritised further investigation of the concept and set up a scoping study led by BGS.

A steering committee of external experts provided strategic, scientific and technical advice to NERC and BGS on behalf of the academic, industry and policy communities. The context for the scoping study is defined by UK net zero emissions policies and industrial decarbonisation strategies, UKRI and NERC drivers, capabilities of international CO_2 storage research facilities and the needs of researchers and the UK industrial clusters planning carbon capture, utilisation and storage (CCUS) projects. This report summarises the scientific challenges this community has identified and the capabilities that a new CO_2 storage research facility could provide to address these.

The steering committee recommended the appraisal of a broad range of options to ensure the scientific case for investment is robust and meets CCUS community needs. They advised that the key research requirements should be defined before design of the infrastructure was considered, to ensure a science-led rather than concept-driven approach. The science case was defined by stakeholder input through a broad and structured consultation process. Clear arguments for and against different options were gathered and assessed.

Initial stakeholder engagement was conducted by interviews and a written consultation to solicit community views from academia, industry, CCUS associations, pilot sites and regulators. The initial engagement informed a draft science case which was subsequently reviewed and assessed by iterative engagement with experts via a questionnaire and two online workshops. The consultation confirmed the UK has no comparable deep CO_2 storage research facilities. Feedback from stakeholders highlighted social science research as a key scoping study element. Subsequent social science sandpit discussions were held which identified themes for societal and cultural research at a CO_2 storage research facility.

The stakeholder community consultation established the key knowledge gaps in research and innovation and defined the scientific challenges that a CO_2 storage research facility would address. The community highlighted key knowledge gaps, not considered by industry or at existing international research sites. The challenges to be addressed at a facility include fundamental scientific investigations, technological advances and societal understanding that are required for the widespread adoption of carbon capture and storage in the UK.

The beneficiaries of a UK CO_2 storage research facility are identified as the UK and international science base and industrial clusters, policymakers and regulators, academic researchers and the offshore workforce. Wider benefits and impact during the anticipated 15 to 20 years operation of a facility are mapped. The political, environmental, social, technical and legal considerations are listed to identify key risks and concerns during future site selection. The planning and permitting constraints and dependencies for a research facility are summarised.

A CO_2 storage research facility has the potential to be a large research infrastructure in scale, ambition, and cost. A computer simulation of the operation of a CO_2 storage research facility has predicted its subsurface dimensions and tested the detectability of injected CO_2. A longlist of research facility infrastructure options is presented that was informed by the stakeholder engagement and ratified by the steering committee. The science case, study objectives and a set of defined critical success factors are to be used as criteria for future down-selection to form a shortlist.

A full proposal to develop a second phase of scoping for a deep geological CO_2 storage research facility was submitted to the UKRI Infrastructure Fund in June 2021. If this full proposal is successful, a second study would further de-risk the delivery of the proposed research infrastructure. Stakeholder engagement has been a key contribution to this scoping study. A second phase of scoping would be dependent on continued engagement with the stakeholder community. A contact point is provided for stakeholders and interested parties who wish to be involved with the scoping of a UK deep geological CO_2 storage research facility.


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1 Objectives of the scoping study

'To deliver a world-leading deep geological CO_2 storage facility for fundamental and applied research and innovative technology development, led by a community view of need.'

Figure 1 CO_2 capture and permanent geological storage plans to reduce CO_2 emissions vented to the atmosphere from large industrial point sources.

The scoping study objective was to identify, through extensive consultation, the unique research requirements for a UK deep CO_2 storage research facility. The research requirement should be coordinated with, and complementary to, existing national and international activities. The study developed a list of achievable, scalable infrastructure options, guided by industry stakeholders. A next phase of the study would include selection of an infrastructure option and a site for a facility.

2 A CO_2 storage research facility scoping review

Scoping study leadership

BGS presented the concept for a deep geological CO_2 storage research facility to the UKRI Infrastructure Fund Announcement of Opportunity (UKRI, 2020b). The concept for a CO_2 storage research facility was prioritised for further investigation by NERC in summer 2020. NERC set up a scoping study in October 2020. BGS was appointed to lead the scoping study. BGS has the responsibility to support national strategic needs and provide impartial leadership to the UK environmental science community, as part of NERC's National Capability remit, and is in an ideal position to lead the community-focused study.

BGS is the UK's premier provider of objective and authoritative geoscientific data, information and knowledge and the scoping study was led by BGS's carbon capture and storage team, which has been a European centre of excellence in CO_2 storage since the mid-1990s. This dedicated expertise provided significant thought leadership to the study and BGS was able to use their extensive networks to support a thorough community assessment of the science, aims and concepts for a CO_2 storage research facility.

Figure 2 BGS headquarters and national core store at Keyworth, Nottingham. BGS © UKRI.

A steering committee of external experts provided strategic, scientific and technical advice to both NERC and the scoping study project management team on behalf of the communities that its members represented. The role of the steering committee was to:

- provide expertise on a wide range of specialisms,
- provide specialist knowledge to steer the strategic direction to
    - maximise benefits for the user community,
    - improve and innovate,
    - ensure that any large investment in infrastructure aligns to current and future demand for environmental research and innovation,
- highlight opportunities for complementarity with other initiatives, both nationally and internationally, including funding and impact opportunities,
- advise on the ways in which the project can best engage with the correct stakeholders and articulate the correct messages, e.g. community science and end-users.

3 Why is a deep CO_2 storage research facility needed?

Why CCUS?

Carbon capture, utilisation and storage (CCUS) involves the capture of CO_2 emissions, primarily from industrial processes and from power generation through the burning of fossil fuels. The captured CO_2 is transported from its source and permanently stored in geological formations deep underground. An experimental subsurface research and innovation facility would enable investigation of the key scientific and technology knowledge gaps for deep geological CO_2 storage.

Permanent geological CO_2 storage is a key technology to prevent increased concentration of CO_2 in the atmosphere and plays a crucial role in mitigating climate change. To meet the ambitions of the 2015 Paris Agreement, there is international consensus that CCUS will be an essential tool in effectively tackling climate change and in achieving the necessary CO_2 reductions in the UK and internationally (Intergovernmental Panel on Climate Change, 2018). CO_2 storage is being evaluated as a necessary response to both long-term strategies and shorter-term policy requirements in the UK, Europe and globally (HM Government, 2021; European Commission, 2019; International Energy Authority, 2021). The UK's Climate Change Committee recommends CCUS must play a significant role if the UK is to achieve national emissions reduction targets (Climate Change Committee, 2020b). CCUS can contribute to a low-carbon future through:

- decarbonisation of industrial processes (Figure 3),
- enabling low-carbon production of hydrogen for heating from natural gas,
- offering a route for negative emissions by storing more CO_2 than a source produces.

To achieve these ambitions, the UK must unlock the potential of the subsurface as the geological storage of CO_2 is central to reaching net zero greenhouse gas emissions targets ('net zero'). Research at a CO_2 storage facility, as part of wider actions to achieve net zero emissions, will focus on:

- increasing knowledge and addressing science gaps,
- informing policy and regulation,
- reducing costs,
- enabling necessary innovation in CO_2 storage.

Strategic drivers for a UK CO_2 storage research facility

The Climate Change Committee (2020a) states that CCUS is a necessity, not an option, in meeting net zero targets. Whilst the UK has made significant progress in recent years in decarbonising specific sectors, achieving net zero by 2050 requires decarbonisation across more sectors, including domestic heating, industry and transport by heavy goods vehicles and rail (Climate Change Committee, 2020b).

CCUS can reduce emissions in many of these sectors as part of broader measures, which include electrification, further efficiency gains and lifestyle adaptations (Climate Change Committee, 2020a). A more recent report to Parliament (Climate Change Committee, 2021) identifies meaningful public

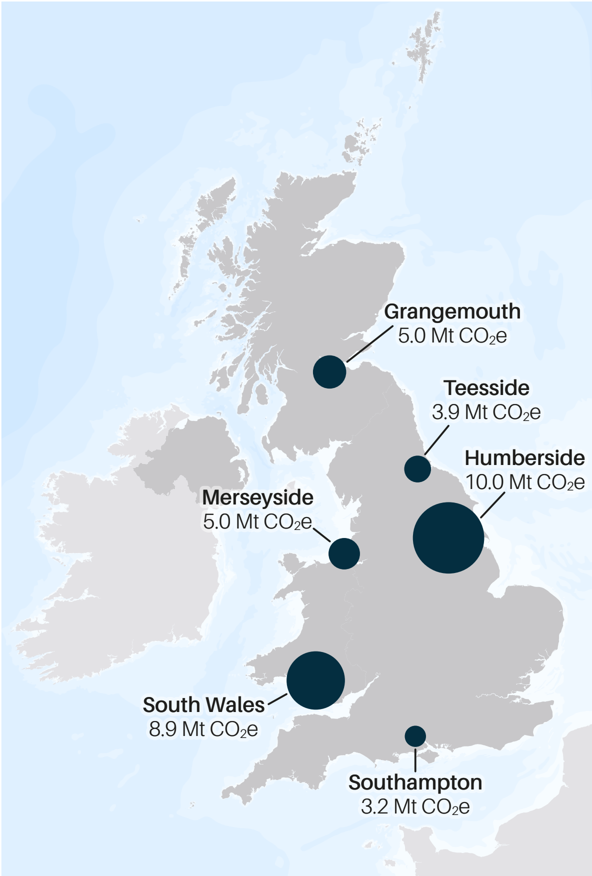

Figure 3 Map of major UK industry cluster emissions in 2018, equivalent to million tonnes CO_2. From HM Government, 2021.

engagement on future changes and their timings will help build stronger public consent for the transition.

The UK Government's 2021 Industrial Decarbonisation Strategy outlines UK policy to achieve CO_2 emissions reductions to meet net zero through CCUS and low-carbon fuels (HM Government, 2021). The Prime Minister's Ten Point Plan (HM Government, 2020a) and subsequent Energy White Paper (HM Government, 2020b) set policy objectives for 10 million tonnes of CO_2 captured by 2030 through £1 billion funding support for four CCUS clusters for co-located clean industry, transport and power (Figure 3).

The first two full-scale CCUS clusters are expected to be developed by the mid-2020s, with the second two clusters developed by 2030. However, this policy falls short of 'Balanced Pathway to Net Zero' (Climate Change Committee, 2020b), which indicates 22 million tonnes of CO_2 should be stored by 2030 across at least five industrial clusters. Therefore, although CCUS is expected to become a reality for the UK in the mid-2020s, it is clear that there will need to be significantly more storage in decades to come, beyond those stores being developed now, to meet current policy up to 2030. **A new UK CO_2 storage research facility will support this wider deployment, address the current knowledge gaps and improve understanding of larger-scale subsurface CO_2 storage deployment.**

The North Sea Transition Deal (BEIS, 2021) sets targets for emissions reductions and outlines how the oil and gas sector can support deployment of hydrogen and CCUS. It includes a commitment to deliver investment of between £14 billion and £16 billion by 2030 for new energy technologies and the consequent support for up to 40 000 direct and indirect supply-chain jobs. The North Sea Transition Deal undertakes to develop robust industry standards. **A new UK CO_2 storage research facility will provide the scientific and operational experience to inform the development of industrial standards in CO_2 storage.** Research at a UK facility will also inform regulation of the deployment of CO_2 transport and storage infrastructure.

Public support requires demonstration that CCUS is an effective strategy in reducing emissions and that it is secure, with a specific focus on demonstrating the containment of geologically stored CO_2 (Wickett-Whyte et al., 2021). Security features should include explicit and accessible communication supported by a strong evidence base, including decommissioning. **A new UK CO_2 storage research facility will provide both the scientific knowledge to inform that debate and the public-facing exemplar of CO_2 storage that will catalyse local, national and international engagement. It would also directly support the development of an evidence base, enable accessible communication, enable testing of site closure, and explain risks as well as benefits.**

A CO_2 storage research facility would provide 'transparent information on safety, costs and funding, the role of CCUS in reaching net zero, local environmental impacts and economic benefits' (Wickett-Whyte et al., 2021).

UKRI and NERC drivers

A CO_2 storage research facility aligns strongly with the UKRI Infrastructure Landscape Analysis (UKRI, 2020a), specifically addressing the requirements to provide environmental capabilities across large spatial scales (micrometres to kilometres) and temporal scales (minutes to millennia). The UKRI Opportunities to Grow Our Capability report (UKRI, 2020b) also identifies CCUS as a priority theme in the energy sector and an infrastructure option in the environment sector.

NERC recognises the need to develop large research infrastructure that directly supports its science priorities and aligns with the NERC Delivery Plan (NERC, 2019). A new CO_2 storage research facility would specifically support the priority areas within the delivery plan by:

- pushing the frontiers of understanding and providing UK environmental science with an ambitious opportunity to undertake world-leading research,
- enabling a shift to a more resource-efficient economy and directly inform economic models of CO_2 storage, which is a key focus of current BEIS policy development
- providing a nexus for cutting-edge technologies (especially if an offshore concept is selected) in:
    - » machine learning and automated data interpretation,
    - » remotely acquired and automated big data management from a range of continuous sensor technologies,
    - » open 'nowcasting' to enable decision making based on real-time feedback from the environment,
- enabling UK science to collaborate more deeply with scientists internationally, both from those countries with an established expertise and capacity in CO_2 storage research and from countries that are developing CCUS technologies,
- providing a step change in UK capability in CO_2 storage and deep geological research and innovation,
- providing a globally unique facility that will enable training of and experience for the next generation of scientists and engineers, who will scale up CCUS,
- helping to attract and retain international and home-grown talent to pursue cutting-edge research.

UK decarbonisation strategy

The UK strategy for decarbonisation of industry is to support deployment of CCUS on industrial sites in clusters (Figure 3) and fuel-switching to low-carbon hydrogen (HM Government, 2021). Large-scale production of hydrogen by reformation of methane from natural gas as a low-carbon technology requires permanent storage of the CO_2 by-product. Planned implementation of hydrogen production and CCUS at UK industrial clusters will generate a notable increase in the CO_2 supplied for geological storage (Akhurst et al., 2021).

During 2021, the UK Government led a cluster sequencing process to identify CCUS clusters whose readiness suggests they are most naturally suited to deployment in the mid-2020s, referred to as 'Track-1 clusters'. Two Track-1 clusters, the HyNet and East Coast clusters, were confirmed to be taken forward to negotiations for support; with the Scottish Cluster as a reserve (UK Parliament, 2021), which is supported by Scottish Government (2022).

The cluster sequencing process will transform Teesside, the Humber, Merseyside, North Wales and the north-east of Scotland over the next decade. The Track-2 cluster sequencing processes will bring forward capture and storage of at least 10 million tonnes of CO_2 per year by 2030.

A new UK CO_2 storage research facility will gather the evidence for the long-term decadal monitoring of injected CO_2 needed for conformance and site closure for regulators and the first UK storage operators (i.e. Track-1). Demonstrating storage site closure will inform future operational policies and the design of the next planned commercial projects (Track-2). Hosting a UK research facility will support training and learning for the future engineers, geologists, regulators, financiers and expertise required to help the UK reach its net zero targets and enable the energy transition. A UK research facility will address specific questions raised by the consultations with industry, regulators and academic researchers.

International CO_2 storage research facilities

A deep CO_2 storage research facility will take advantage of the UK's existing knowledge and capability. Since 2011, the Government has invested over £130 million in CCUS research, development and innovation through the CCUS Innovation Programme and its predecessors (BEIS, 2013). UKRI has commissioned over 130 research projects specifically in CCUS. EPSRC's UK CCS Research Centre has over 1400 academic members, demonstrating the large and active research community, and an operational CO_2 'capture' research laboratory (pilot-scale advanced capture technology or PACT).

A landscape review assessed international CO_2 storage pilot and demonstration sites and their capability to address the UK science case (Figure 4). The study evaluated sixteen key international pilot and demonstration sites at which CO_2 storage research has been undertaken, in:

Australia	Japan
Canada	Norway
Denmark	Switzerland
Germany	UK
Iceland	USA

The review found that each of the international pilot and demonstration sites was designed, constructed and operated for the site to answer specific priority research questions. At three of the sites, this took place when CCUS was a largely nascent research topic:

- Sleipner, Norway
- Ketzin Pilot Injection Site, Germany
- Frio Brine Pilot, USA

Once operational, there is limited flexibility in how these existing storage sites can adapt to emerging research questions. Although overlap exists, none were developed explicitly to support commercial CCUS deployment in the UK.

Three international pilot and demonstration sites have also completed their planned operations and research:

- Frio Brine Pilot, USA: completed injection in 2006
- Ketzin Pilot Injection Site, Germany: completed in 2013
- Illinois Basin Decatur Project, USA: evolved into a commercial-scale project

A UK facility should be designed to build on research published by international industry projects and conducted at current and completed research sites. Operation of a UK research facility should be complementary to investigations by industry and at international pilot and demonstration sites.

Seven of the international pilot and demonstration sites were designed to address specific challenges associated with CO_2 storage. Five examine leakage or overburden processes:

- Mont Terri CS-D Experiment, Switzerland
- Svelvik CO_2 Field Lab, Norway
- QICS controlled release experiment, UK
- GeoEnergy Testbed, UK
- Field Research Station, Canada

Their focus is on the near-surface strata overlying a storage formation and, therefore, cannot be used to address the science objectives related to demonstrating deep, permanent CO_2 containment.

Of the other two projects, the Icelandic CarbFix Pilot Project stores CO_2 via in situ mineral carbonation in basalt rocks. Owing to the presence of extensive sandstone formations in the UK, basalt storage is not currently being considered and research at the CarbFix Pilot Project is not a suitable analogue.

Finally, the Australian CO2CRC Otway Project is also not directly comparable as the injection stream comprises 80 per cent CO_2 and 20 per cent methane. This CO_2 concentration is lower than anticipated for commercial UK CO_2 storage, potentially affecting flow assurance, trapping mechanisms and long-term stability of the injected CO_2.

The UK has significant offshore CO_2 storage potential (Bentham et al., 2014), well-known from oil and gas exploration and production data. Plans for CO_2 storage from UK industrial clusters are within offshore, deep, saline water-filled sandstone formations and depleted hydrocarbon fields. Many of the pilot and demonstration sites in North America and Australia are onshore, e.g. Illinois Basin Decatur Project, the Canadian Field Research Station and the Australian CarbonNet Project. Findings at onshore sites are not analogous to UK plans for offshore CO_2 storage.

Application of the monitoring technologies, remote data acquisition and physical access to an offshore site present challenges to UK industry for cost-effective optimal monitoring. Of the 16 projects reviewed, only four test the storage of CO_2 in an offshore setting:

- Project Greensand, Denmark
- Sleipner, Norway
- Snøhvit, Norway
- Tomakomai CCS Demonstration Project, Japan

Sleipner and Snøhvit are commercial projects owned and operated by Equinor. At these sites, CO_2 storage is secondary to hydrocarbon production; naturally occurring CO_2 is processed and removed from the production stream and re-injected into saline water-filled sandstone formations. Although these sites are of substantial interest to the research community — for example, there is an extensive modelling-monitoring conformance campaign at Sleipner — they are limited due to their commercial operation. Moreover, injection of CO_2 at Sleipner and Snøhvit began in 1996 and 2008, respectively, and many novel science objectives could not be addressed at these sites.

Similarly, Project Greensand is intended as a commercial project led by INEOS Energy as part of a consortium that includes Maersk Drilling and Wintershall Dea. Project Greensand will not assess saline water-filled sandstone storage, which is a key requirement for UK CO_2 storage, and many key science objectives cannot therefore be assessed at this site.

None of the international sites considered conformance, policy development or regulations for site closure. Each considers public engagement for their own population and not the perception of the UK public and its awareness of CO_2 storage to reduce emissions.

The review did not identify any existing research infrastructure suitable to address the science questions associated with the commercial deployment of CCUS planned in the UK that were raised by the community consultation.

Figure 4 Operational CO_2 storage research site at Otway, Australia. Ceri Vincent © BGS.

The CO_2 storage stakeholder community view is for offshore CO_2 storage research at industrially relevant scales, to address fundamental and applied science and technology questions (Section 4). All UK industrial clusters that submitted plans to the BEIS cluster sequencing competition intend to operate offshore at rates to achieve a total of tens of million tonnes stored by 2030.

A recent proposal for a UK net zero academic and industry partnership, Research Infrastructure for Subsurface Energy (or 'Net Zero RISE'), aims to repurpose existing, onshore oil and gas deep-well infrastructure as test sites. Net Zero RISE intends to use these onshore wells as cost-effective facilities to develop and test CO_2 and hydrogen storage and geothermal technologies. The first proposal for initial investigation of onshore UK storage in depleted fields by Net Zero RISE is complementary to the objectives to support planned clusters. Discussions with the partnership members would ensure mutual benefits for both proposed facilities.

As the CCUS industry evolves, it is important that international collaboration and alignment across research programmes is promoted, facilitating knowledge sharing and the development of the UK's CCUS research and innovation capabilities and reputation. Nevertheless, there remains a clear need for a standalone UK deep CO_2 storage research facility to address the novel and emerging science objectives specific to the commercial deployment of CCUS in the UK. A UK facility would ensure there is alignment with research undertaken at decommissioned, existing and upcoming international research capabilities whilst striving to combine and complement findings in order to maximise the growth of CO_2 storage across the globe.

In summary therefore, there is sufficient evidence from this review to support the development of a standalone UK subsurface CO_2 storage research facility. Alignment and complementarity with international pilot and demonstration sites will ensure the combined efforts best serve the growth of the CO_2 storage industry both in the UK and abroad. Discussions with international facilities will ensure a facility aligns with international programmes to leverage collaboration and establish the UK as a world-leading nation for researchers to conduct cutting-edge research.

Research objectives for the CO_2 Storage Testbed

The scoping study developed objectives for a research facility through extensive community engagement (See Chapter 4) and with expert input from BGS and NERC (**Table 1**).

Table 1 Objectives for a CO_2 storage research facility.

Objective
To increase the understanding of CO_2 storage processes relevant to commercial deployment both in the UK and internationally.
To support innovation in CO_2 storage technologies that will lead to increased assurance of containment and/or cost reductions in CO_2 storage operations in the UK.
To provide independent, science-based evidence to improve policy and regulations in CO_2 storage, specifically with regards to site closure.
To enable open and transparent dialogue with diverse public groups in order to increase the awareness and understanding of CO_2 storage and its role in industrial decarbonisation.
To create a world-leading, strengthened and cohesive CCUS community within the UK, deepening and widening collaboration with the international research community.
To support industry in their plans for CCUS through collaboration, innovation, knowledge exchange and training.

4 CO_2 storage research community view

The steering committee recommended that a full appraisal of a broad range of options would ensure the scientific case for investment was robust and met the needs of the CCUS community. They also recommended that the scoping study should define the key research requirements before considering the infrastructure required to deliver them, thereby ensuring the project is science led rather than concept driven. The scoping study established the science options using input from stakeholders through a broad and structured consultation process. Clear arguments for and against different options were gathered and assessed during the stakeholder consultation process.

The scoping study undertook extensive community consultations, garnering responses on the requirements for a CO_2 storage research and innovation facility from stakeholders in research and industry and the regulator and policy, commercial and international sectors.

The views of stakeholders were solicited in a three-phase engagement strategy to inform the science case. Bilateral online interviews with stakeholders, identified by BGS and the steering committee, were conducted with the aim of developing scientific objectives and design features relevant to the research requirements. In total, 27 interviews were held from November 2020 to January 2021, with 56 people representing the academic, commercial, industrial, advisory and regulatory sectors.

Views were then summarised in a document used in a broader, written consultation process open to all interested parties. Notice of the intended consultation and invitation to register were posted as a news item on the BGS website in March 2021 and widely circulated via industry associations. Thirty-five responses were returned in April 2021 from stakeholder organisations within academia, industry, pilot sites and associations, each representing multiple respondents (Table 2). An assessment of the outstanding scientific knowledge gaps collated from the written consultation responses was presented as a draft science case and distributed to the stakeholder community. The draft science case was reviewed and assessed by iterative engagement with the experts via a questionnaire and two online workshops.

Workshop participants came from a broad range of stakeholders (Figure 5). They were asked to respond to a questionnaire, which was also made available to those unable to attend. Responses to the questionnaire indicated broad agreement that the science case accurately summarised the community view. Over 80% of the workshop participants agreed or strongly agreed that the science case clearly states the challenges faced in CO_2 storage. No respondents disagreed with the science case content.

Respondents were also asked to indicate their priorities for science research themes to inform cost-effective deployment of UK CO_2 storage (Figure 6). They highlighted the breadth of science covered in the science case and the discussion groups mainly highlighted areas where further detail was required rather than missed topics — this is expected as the draft science case reflected the community view.

The consultation confirmed the UK has no comparable deep CO_2 storage research facilities.

The stakeholder community identified that the absence of a subsurface storage research facility limits UK capability to build on investments and deliver the next stage in CO_2 storage research. They noted that the science case reflects the outcomes of the consultation exercise.

Table 2 Stakeholder organisation respondents to the written consultation.

Stakeholder group	Organisation
Research	• Netherlands Organisation for Applied Scientific Research (TNO), Netherlands • Imperial College London and UK CCS Research Centre, UK • Energy Research Accelerator and University of Nottingham, UK • Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), Italy • University of Portsmouth, UK • Royal Holloway University London, UK • Centre for Research and Technology Hellas (CERTH), Greece • Geological Survey of Denmark and Greenland (GEUS), Denmark • University of Cambridge, UK • University of Oxford, UK • University of Edinburgh, UK
Association	• International Energy Authority Greenhouse Gas R&D Programme • European Research Infrastructure for CO_2 Capture, Utilisation, Transport and Storage (ECCSEL)
Key industry player	• INEOS • Pale Blue Dot • ENI • Equinor • iGAS • Schlumberger • Drax
Pilot site	• Fundación Ciudad de la Energí (CIUDEN), Spain • Carbon Management Canada Research Institutes, Canada • University of Texas, USA
Regulator	• Environment Agency, UK

Workshop participants also expressed satisfaction through the following feedback:

- 'Thank you for leading on such a great workshop today [...] It was great to hear such a wide and varied discussion around some of the complexities around site characterisation and monitoring.'
- 'Hearing the discussions really helped clarify some of the priority areas for me.'
- 'Thanks for the workshop, it was interesting to consider the key science requirements and the break-outs enabled some detailed discussions.'
- 'Really positive and the discussion groups I was in provided some really useful steers on areas of importance.'

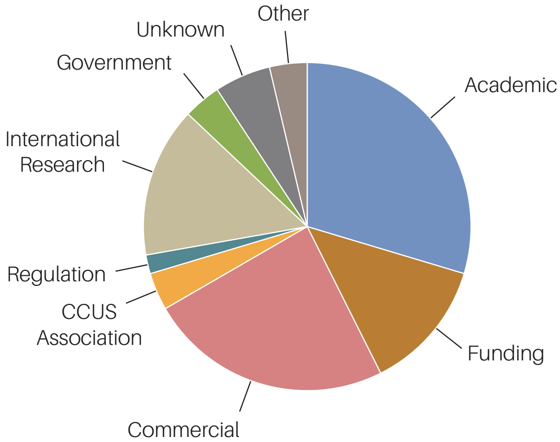

Figure 5 Workshop participants by stakeholder group. BGS © UKRI 2022.

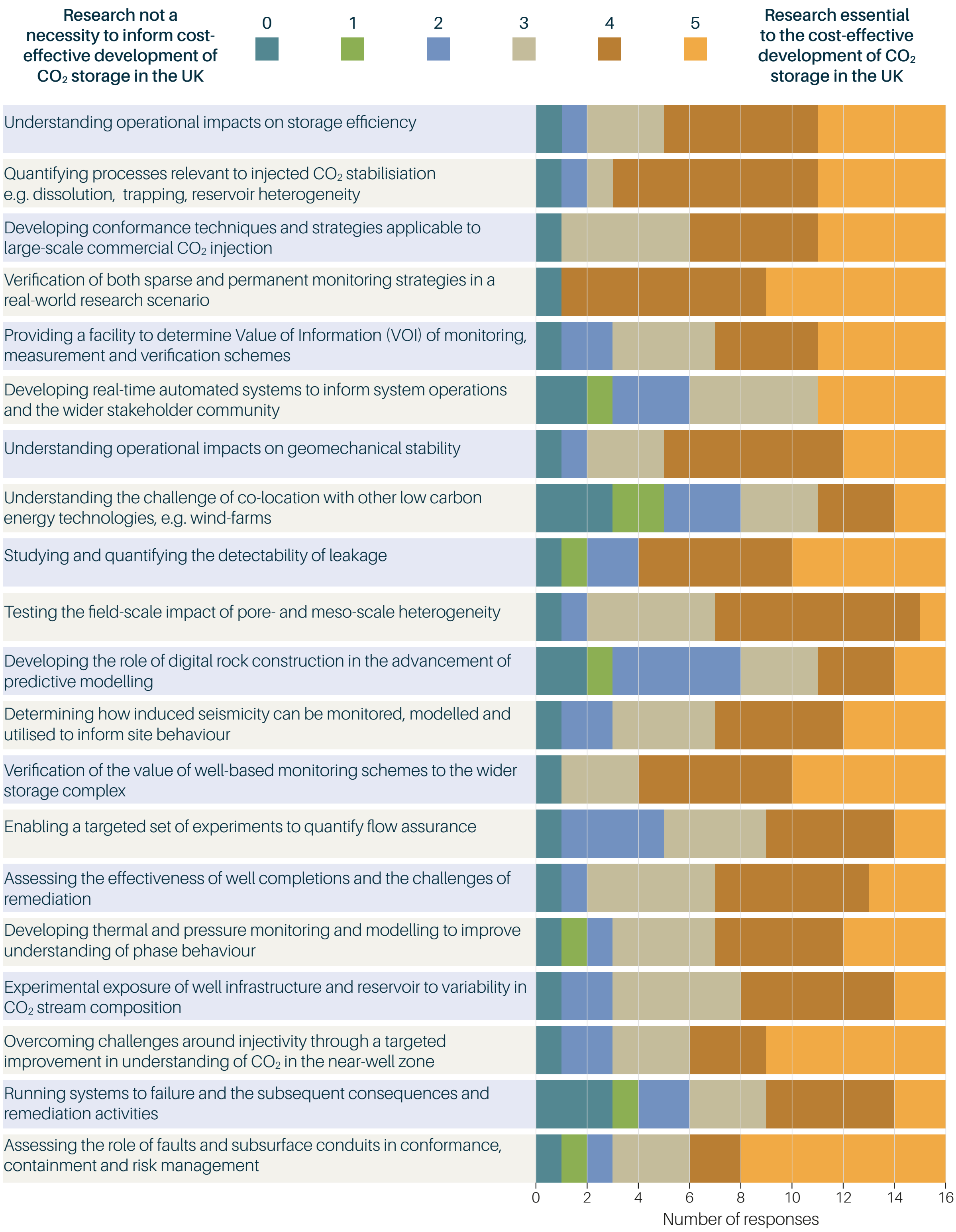

Figure 6 Questionnaire responses on the prioritisation of research themes to inform cost-effective deployment of UK CO_2 storage. BGS © UKRI 2022.

Social science engagement

A new CO_2 storage research facility would provide a unique opportunity to take a truly interdisciplinary approach during each phase of its development. Feedback from the preceding stakeholder engagement with technical stakeholders highlighted social science research as a key element of the scoping study. They advised design of a facility should include social science research in site characterisation, operation and monitoring activities. A social science online 'sandpit' was organised as a first step to develop a network of diverse social science, arts and humanities researchers to explore new, exciting and unexpected research opportunities (Napier et al., 2022). Twenty-nine external participants attended from UK and Netherlands universities and public sector organisations. All participants engaged fully and many contributed additional insightful comments. All present showed real enthusiasm for the activities and provided positive feedback after the event:

- 'Thanks so much for the invite to this amazing sandpit! […] please do keep me in mind for future directions of travel.'
- 'Nice group of experts and very inspiring conversations.'
- 'Great experience, compact but a great joy to hear so many great ideas and discussing them. Would be great to see how this is received by the "Science and CCS [carbon capture and storage] community".'
- 'The breakouts were probably the most interesting and inspiring I have participated in.'

The sandpit was viewed as the start of the process to design social and physical science research areas and questions, to maximise UK societal benefit from a dedicated research and innovation facility. Continued engagement with social scientists should enable the definition of research questions for a future facility.

Outcomes

Social science, arts and humanities researchers welcomed the opportunity that a CO_2 storage research facility would provide as a platform to conduct their own research. They emphasised it would be novel and vital to engage social sciences, arts and humanities researchers early in the process; to contribute to early thinking on the siting of a facility and to gather qualitative data for social baseline assessments in conjunction with the scientific and technical characterisation. Early integrated and interdisciplinary research and engagement, alongside geoscience research, was seen as innovative and novel. Many attendees had experience of other large projects that had tried and failed to embrace a truly interdisciplinary approach. The sandpit discussion was seen as an exciting step forward in terms of integration and collaboration across disciplines.

There was particular emphasis on the role of arts and heritage in the communication of, and engagement with a research facility. Additional strong themes that emerged included existing narratives, place-based research, energy justice and fairness, futures literacy and governance and policy. This event was not only viewed as the start of the process to plan the research aligned with a CO_2 storage research facility, but also that it would enable wider conversations around the research facility's potential contribution to a timely and fair energy transition, as well as the wider issues of carbon mitigation and net zero.

Research themes and questions identified during the discussions were shared and confirmed with participants after the sandpit. The emerging priority research themes reflect all discussions held at the sandpit (Table 3); the relevance and potential impact of the research are explored in Napier et al. (2022). Timely development of an interdisciplinary research programme and funded support are included in the recommendations from the sandpit (Napier et al., 2022).

Table 3 Emerging research themes at a CO_2 storage research facility from sandpit discussions.

Societal and arts and humanities research themes
Role of culture and heritage fossil fuel identities
Place-based and participatory research
Value of tacit and indigenous knowledge, experience and collective memory
Energy justice and the just transition
Energy futures, timescales and futures literacy
Governance
Trade-offs, benefits and risks
Social conflict and trust
CO_2 storage narratives
Creative and arts-based approach to engagement and communication
CO_2 storage research facility as a 'public laboratory'

Conclusions from the sandpit discussions

A CO_2 storage research facility provides a unique opportunity to take a much more integrated approach to research that transcends the traditional boundaries between different research councils. We know that public opinion can matter, particularly when it comes to development of energy policies both locally and nationally. Therefore, it is crucial to approach scoping of a facility holistically through different yet complementary work streams. Societal and cultural workstreams should consider opportunities when building and using a storage research facility, to initiate diverse conversations and widen engagement. They should also consider the challenges of risks and decisions in an uncertain environment that will come into play at key points in its development. They should progress alongside activities to address the scientific opportunities and technical challenges. Taking this integrated approach will create a greater chance of achieving positive impact by:

- enabling community agency in the development and co-design of a CO_2 storage research facility,
- encouraging dialogue and investment in CO_2 mitigation strategies and localised behaviour change in support of the transition to net zero,
- embedding an understanding of the role CO_2 storage could play in the energy transition alongside other complementary carbon reducing strategies,
- enabling positive, transparent and inclusive energy policy development both locally and nationally.

5 CO_2 storage science case

The stakeholder community consultation established the key knowledge gaps in research and innovation, and defined the scientific challenges that a CO_2 storage research facility would address.

CO_2 storage knowledge gaps

The community consultation highlighted key knowledge gaps, not considered by industry or at existing international research sites, that a CO_2 storage research facility could uniquely address:

1. *Understanding real-life operational impacts on long-term storage efficiency to improve storage security and reduce risks and costs* e.g. What are the impacts of different injection strategies and stream compositions on borehole integrity, injectivity, flow assurance, storage efficiencies and long-term containment?
2. *Improving knowledge of subsurface geological processes at scale* e.g. What are the most significant processes on CO_2 plume stabilisation such as dissolution and other trapping processes and the impact of reservoir heterogeneity, in operations and storage site closure to meet stakeholder and regulatory requirements? How can these different mechanisms be robustly quantified?
3. *Determining the necessary level of site characterisation to ensure maximum value of information is achieved in subsequent experimental campaigns* e.g. what needs to be known upfront for cost-effective monitoring strategies to deliver sufficient detail to understand subsurface behaviour during injection and post-injection activities.
4. *Cost-effective monitoring, conformance technologies and development of equipment and services* e.g. Ground-truthing remote and indirect sensing technologies through advanced subsurface monitoring to validate reservoir behaviour and quantify possible leakage; testing well-based monitoring, including fibre-optic technologies, beyond current limits to assess far-field processes; and developing real-time automated decision making.
5. *Monitoring technology, environmental research and strategic management of different UK low-carbon energy uses* e.g. How can monitoring for CO_2 storage be optimised when co-located with other energy transition uses, e.g. wind farms? How can we minimise the environmental impacts of CO_2 storage on the living and physical environment?
6. *Social attitudes to local hosting of major 'Net Zero' infrastructure as well as citizen science opportunities beyond CO_2 storage* e.g. what can the creation of a large CO_2 storage research facility tell us about what the local community feels their role is in addressing climate change? How can we co-design and co-produce research programmes with the community? How can environmental humanities research interests, such as the human elements of, and social attitudes towards, climate adaptation and mitigation, be addressed at a research facility?

CO_2 Science challenges

The views of stakeholders, that were raised in the early engagement and confirmed by the stakeholder workshops, inform and determine the outstanding research questions of the science case. A deep, CO_2 storage research facility must address these fundamental unknowns to inform the permanent geological storage of CO_2 and its deployment in the UK. The challenges to be addressed by research include fundamental scientific investigations,

Table 4 Science challenges to be addressed by a UK deep CO_2 storage research facility.

Science challenge: science case of outstanding CO_2 storage research questions
How can different injection strategies improve the efficiency of storage and confidence in the containment of injected CO_2?
Which trapping mechanisms contain the injected CO_2 in the subsurface and how much is trapped by each mechanism?
How can we increase confidence in the scale-up of research results on the storage formation, from microscope-scale observation and analysis to site-scale application?
How do we make monitoring, conformance technologies, leakage detection and development of equipment and services more cost-effective?
How can we minimise the environmental impacts of CO_2 storage on the living and physical environment?
How can we better engineer and monitor the well and the near-well zone?
How can the footprint of CO_2 storage site monitoring be minimised to reduce conflicts of use of the seabed?
How can we increase the certainty of operation and containment at CO_2 injection wells?
How can we increase understanding of leakage and overburden processes?
How can we understand social attitudes to local hosting of major net zero infrastructure as well as engage citizen science opportunities beyond CO_2 storage?

technological advances and societal understanding that are required for the widespread adoption of carbon capture and storage in the UK, and are presented in Table 4.

Who are the beneficiaries of a UK research facility?

UK science base

The construction, operation and closure of a CO_2 storage research facility would create a world-class testing ground for deep subsurface monitoring sensors and technologies. It would advance UK CCUS research and other applications where advanced subsurface monitoring is required, such as geothermal energy. Other UK science research communities and sectors that will benefit include:

- marine and terrestrial geology and geophysics,
- geochemistry,
- remote sensing and technology,
- earth observation,
- environmental computational modelling,
- predictive software development.

The UK offshore CO_2 storage capacity exceeds expected UK capture rates (Bentham et al., 2014; Akhurst et al., 2021) and is sufficient to provide a storage service for other European countries where geological resources are more limited. A deep borehole research facility would position the UK as a leading nation in CO_2 storage and predictive modelling capabilities. A new facility would provide clear leadership to other countries exploring the feasibility of CO_2 storage.

UK industrial clusters

The challenges that comprise the science case are the research needs identified by industry and regulatory stakeholders together with researchers. The outcomes of research to address the science challenges (Table 4) would be undertaken in industry and/or academic research collaborations to enable direct support of UK net zero ambitions. This support would include risk reductions, improved stakeholder confidence and cost reductions directly relevant to the decarbonisation of UK industrial clusters.

UK policymakers and regulators

Sites are expected to operate to reduce emissions from industrial sources for decades. Uniquely, a UK CO_2 storage research facility would better inform UK policy and regulations for the full lifecycle up to the closure of an operational offshore CO_2 storage site. No other research facility would address the challenges of site closure. The assurance and evidence required for handover of a site and any liabilities, from the operator to the competent authority, will not be considered by an operational commercial site over the coming decades. A research facility will consider the monitoring, degree of conformance with forecast performance and evidence sufficient to close a site, relevant to the operator, regulator and the national authority.

Partnership-working with BEIS and regulators during the operation of a research facility would inform and improve policy and regulation on conformance for site closure. Increased certainty over agreement of conformance at the commencement of or before injection at UK Track-1 and Track-2 industry projects, respectively, would reduce operational costs for the lifetime of the project and concerns regarding liabilities at closure.

UK researchers

A UK research facility would provide UK-based researchers enviable access to a real, field-scale CO_2 storage project. It would enable hands-on training by allowing research to be delivered by the academic, technology development and industry sectors, alongside doctoral students and early-career researchers in earth, social and engineering sciences. UK-based researchers could address the science challenges (Table 1) and knowledge gaps (Section 5.1) identified by this scoping study, including research on:

- CO_2 storage reservoir characterisation, simulation and monitoring,
- social perception of CO_2 storage to reduce emissions,
- design and optimisation of injection strategies,
- well design and operation,
- low-carbon energy systems.

UKRI and community-led training opportunities would be explored as the research programme progresses.

UK offshore workforce

The highly significant UK offshore CO_2 storage resource is known from the data acquisition, experience, knowledge and expertise of the UK hydrocarbon sector workforce. Research at a facility would inform and accelerate offshore geological CO_2 storage and promote adaptation and re-skilling of the UK workforce. Adaptation of the expertise and training of artisans and technicians from the oil and gas sector for CCUS is essential to enable the net zero economy in the UK.

Benefits of a UK research facility

The benefits of the research findings, public awareness activities and technology development at a UK CO_2 storage research facility are over the medium term during the anticipated 15 to 20 years of operation of the facility, and the long term in the decades after the facility has closed. A logic model has been used to frame the benefits of a CO_2 storage research facility, an extract of the benefits mapping is shown in Table 5.

Research at a facility would encompass:

- site characterisation and operation,
- monitoring for conformance during and after cessation of injection,
- site closure and eventual facility shutdown.

In the medium term, during and after completion of research operations at a facility, the beneficial impacts (Table 5) for changes in behaviour, decision-making and actions are anticipated to be:

- knowledge gained,
- increased economic opportunities,
- greater societal awareness of the role of CO_2 storage in the industrial energy transition.

The knowledge gained from the research would be directly applicable to CO_2 storage operators

Table 5 Benefits mapping, excerpt from the logic model for a CO_2 storage research facility.

Outcomes	Impacts (medium-term)	Impacts (long-term)
Increased understanding of storage processes Increased access to fundamental and verified geological datasets for all Improved & Innovative technologies relevant to the UK and international projects World-leading, strengthened and cohesive CCUS community Improve UK CCUS regulation and policy development, especially for site closure. Inform publics on processes and technologies that support secure and permanent CO_2 storage. Increased feasibility of international CO_2 storage deployment	**Knowledge** • UK leadership in science, technology and CO_2 storage • Export of UK technological innovation and expertise • Geoscience enables ethical transition to net zero economy **Economy** • Increased CCUS commercial viability (lower risk, higher efficiency, more secure) • Net zero-technologies evaluated for UK and international decarbonisation • UK CO_2 import and storage income stream **Society** • Re-skilling expertise to support Net Zero • Public and stakeholder support/awareness creating advocates for CCUS • Support to UK govt aim to lead in environmental goals	UK policy fit-for-purpose especially for closure & post-closure liabilities Public and stakeholder (regulator & industry) confidence in secure CO_2 storage Secure and cost-effective CO_2 storage of UK industry cluster emissions CCUS makes a significant contribution to UK achieving net zero Sustainable UK CCUS industry UK global technology leader in CO_2 storage UK is a science superpower

and regulators at UK industrial clusters, allowing leadership in the understanding of underpinning science, the technology developed and the whole lifecycle of CO_2 storage operations. Both the knowledge of the innovative technology developed and the expertise gained from operation and closure phases of the facility are exportable.

Geoscience research, engineering and technology development, and social science investigations conducted and completed at a facility would inform and enable a just and ethical transition to a net zero emission economy for the UK. Monitoring after cessation of injection would also inform regulation of site closure decades before completion of CO_2 storage operations at sites planned by UK industrial clusters.

The benefits to the UK economy are the increased certainty, evaluation and growth of CO_2 storage as a commercial, low-carbon technology. Relevant research and demonstration of innovative technologies at a UK facility at a scale and complexity of a commercially operating site would increase the viability of CO_2 storage by lowering commercial risk, increasing efficiency of operation and assuring more secure and permanent subsurface containment. CO_2 storage as a net zero technology will have been evaluated specifically for decarbonisation of UK industry and also for an international audience, paving the way for a UK CO_2 import and storage income stream capitalising on our significant national geological storage resource.

Societal gains from a UK CO_2 storage infrastructure facility include:

- re-skilling the workforces at industrial clusters with the expertise to support net zero growth, as part of the UK strategy for decarbonisation by CCUS,
- creating an awareness within the public and stakeholders of CO_2 storage as a clean technology,
- supporting employment and economic growth,
- creating local and national advocates,
- providing research findings and monitoring data from the facility to support the UK Government,
- aiming to lead in attainment of environmental goals by large-scale implementation of CCUS.

In the long term, in the decades after completion of injection and closure of a CO_2 storage research facility, the beneficial impacts to the UK would be relevant to policy, emissions reduction, sustainable industry, technology and scientific leadership. UK regulation of the operation of CO_2 storage will be informed by research findings, especially for closure and post-closure liabilities. The beneficiaries would be the operators and regulators of commercial CCUS projects that are planned to operate into the coming decades, affording them confidence in the process and eventual terms of closure for their sites. The operation and closure of the facility would give the UK public and stakeholders confidence in the secure containment of geologically stored CO_2, as a cost-effective technology to reduce emissions from industrial clusters to meet the UK targets by 2030 and net-zero emissions by 2050.

Long-term economic and environmental benefits from research and innovation at a UK CO_2 storage research infrastructure include making a significant contribution to the UK's achievement of national net zero emissions reduction targets. UK strategy is to deliver decarbonisation at four industrial clusters by 2030 and achieve CO_2 emissions reduction of at least 10 million tonnes per year by CCUS (Section 3.2).The impacts from a CO_2 storage research facility would deliver a more cost-effective (Figure 6) and sustainable UK CCUS industry. The technology development and scientific research conducted at a CO_2 storage facility would place the UK as a global leader in the technology and a science superpower for CO_2 storage.

Consideration of risk for site selection

The scoping study considered the key risks and concerns when siting the infrastructure for a deep geological CO_2 storage research facility, whether onshore or offshore. The considerations listed in Table 6 were reviewed to identify key risks and concerns for future site-specific risk assessment. Economic risks were not considered as a site would be selected on the basis of the science case and the infrastructure to gather data to address the science case.

Planning and permitting constraints and dependencies

A planning and permitting review identified requirements that would be considered for development of a CO_2 storage research infrastructure facility. The key planning requirement would be planning permission, including an Environmental Impact Assessment. For permitting, the requirement for a CO_2 storage permit requires further discussions with the North Sea Transition Authority, although a permit may not be required for a research facility injecting less than 100 kilotonnes of CO_2. Environmental permits will be required from the Environment Agency; it is recommended that relevant design and construction considerations required by the Offshore Installation and Wells Regulations (HM Government, 1996) and Borehole Sites and Operations Regulations (HM Government, 1995) are followed, even if they are not formally required. Early consultation with the relevant regulatory authorities is needed to establish requirements and dependencies to ensure timely planning and permitting activities for a deep geological CO_2 storage research facility.

Table 6 Political, environmental, social, technical and legal considerations reviewed to identify key risks when siting a deep geological CO_2 storage research facility.

Political considerations	
Political views of leading councillors/MPs	Local development plans in terms of council support for new energy technologies
Political views of parties relating to CCUS	Local carbon management plans
Proximity to existing CO_2 storage projects and stakeholders	Focus or awareness of CCUS within Local Enterprise Partnership
Local environmental groups	
Environmental considerations	
Ecological value, biodiversity of site and neighbouring areas	Land designation: • national parks • green belt • Sites of Special Scientific Interest • Areas of Outstanding Natural Beauty • National Nature Reserves • Special Areas of Conservation • Special Protected Areas
Ecological surveying requirements	Soils; best and most versatile land
Proximity to ecological receptors	Bombing ranges
Offshore ecology	Coastal erosion — minimal needed
Noise and vibration receptors/limitations	Coastal designations
Light impacts	Air quality, dust and particulates
Traffic impacts	Surface water and groundwater
Landscape and visual impacts, including non-statutory local landscape designations	Climate change, impact on development from extreme events, etc.
Contaminated land	Waste disposal; waste water
Archaeology	Neighbouring planned developments
Unexploded ordnance on seabed and onshore	Neighbourhood plans
Shipwrecks	Land height at wellhead
Rig heights/construction heights	Tidal range
Offshore activities that may interfere with seismometers	Depth to storm wave base

Social considerations	
Proximity to residential areas	Fishermen to avoid dragging scientific monitoring kit along the seabed
Key local stakeholders	Beach users
Proximity to CO_2 generator	Supportive landowners
Place agenda, providing opportunities for jobs, skills, education	
Technical considerations	
Geological suitability	Local water supply
Distance from shore	Accessibility of local road network
Hydrogeological site condition	Highway safety
Availability of sufficient space for operation	Likely permitted construction hours as likely to require 24-hour operation
Distance of a facility from coast (3 km) or geological basin of interest	Decommissioning
Land height at wellhead	Security
Ground investigation around wellhead	Proximity to waste water disposal
Landscape/residences on land above borehole drill trajectory	Beach conditions conducive to cable crossings
Power supply, on- and offshore	Cliffs
Legal considerations	
Access routes to wellhead	Environment Agency seabed constraints
Cross-beach access	Shallow gas, natural biogenic sources
Likelihood of being able to agree Heads of Terms for lease	Legally binding land use restrictions and covenants
Permitting requirements	Planning and Environmental Impact Assessment
Ownership of seabed	Wayleave between beach and wellhead
Seabed access rights for mineral exploration/ exploitation	EU storage directive storage permit required if more than 100 000 tonnes of CO_2 are stored
London Protocol requirements for the management of transport and storage of CO_2	

6 Research infrastructure options

The design of a research infrastructure would be determined by the science challenges defined by the CCUS community (Table 4). Initial scoping-study computer modelling assessed the amount of CO_2 to be injected to address challenges in the science case (Section 6.1). The findings of the modelling were used to inform research infrastructure options (Section 6.2).

Predicting operation of a CO_2 storage facility

A short computer modelling study to understand the likely subsurface footprint of a deep geological CO_2 storage research facility has been undertaken (Figure 7). A three-dimensional model of geological strata suitable for CO_2 storage at depths greater than 800 m, as planned for UK industrial clusters, was used to predict injection at a research facility. At this depth, the CO_2 is a dense, rather than a gaseous, fluid. The computer simulation of CO_2 injection also investigated the mass of CO_2 sufficient to be detectable by site monitoring.

The outcomes of the study provided stakeholders with:

- a representation of the anticipated subsurface extent of injected CO_2 using a suite of potential injection scenarios,
- a range of predicted subsurface dimensions of the injected CO_2,
- an indication of the rate at which the CO_2 spreads out within the subsurface,
- a tool to assess the area to be monitored at a research facility,
- a test of the detectability of dense CO_2 in a gently inclined sandstone formation that is typical and suitable for CO_2 storage in the UK.

Computer simulations considered injection of 15 000, 30 000 or 60 000 tonnes of CO_2 within a three-year period to predict the subsurface dimensions of the injected CO_2. The geological models were also varied, using seven different scenarios spanning an appropriate range of properties that would be reasonable to expect for a storage formation sandstone. The resultant 21 simulations represent a realistic expectation of injection at a UK research facility, limited to a maximum injected mass of 100 000 tonnes of CO_2. Additionally, they approximate the injection profiles at the Ketzin CO_2 Pilot Injection Site in Germany, building on and benefitting from existing published research and ensuring the transferability of the findings to a wider audience.

The width of the injected CO_2 and its height above the injection point in the subsurface were calculated for the simulations. For the smallest mass of CO_2 injected (15 000 tonnes) the maximum predicted width after injection was between 68 and 180 m and the maximum predicted height between 30 and 210 m, whereas for the largest mass of CO_2 injected (60 000 tonnes) the maximum predicted width was between 120 and 355 m and the maximum predicted height was between 43 and 224 m.

Seismic survey data are commonly used to monitor the presence and extent in the subsurface of injected CO_2. Modelling the response of seismic survey sound waves to the presence of CO_2 at different saturations indicates whether it will be detected by subsurface monitoring. A series of different fluid mixing principles were tested. An assessment was then made as to whether the CO_2 would be detected solely by repeated seismic

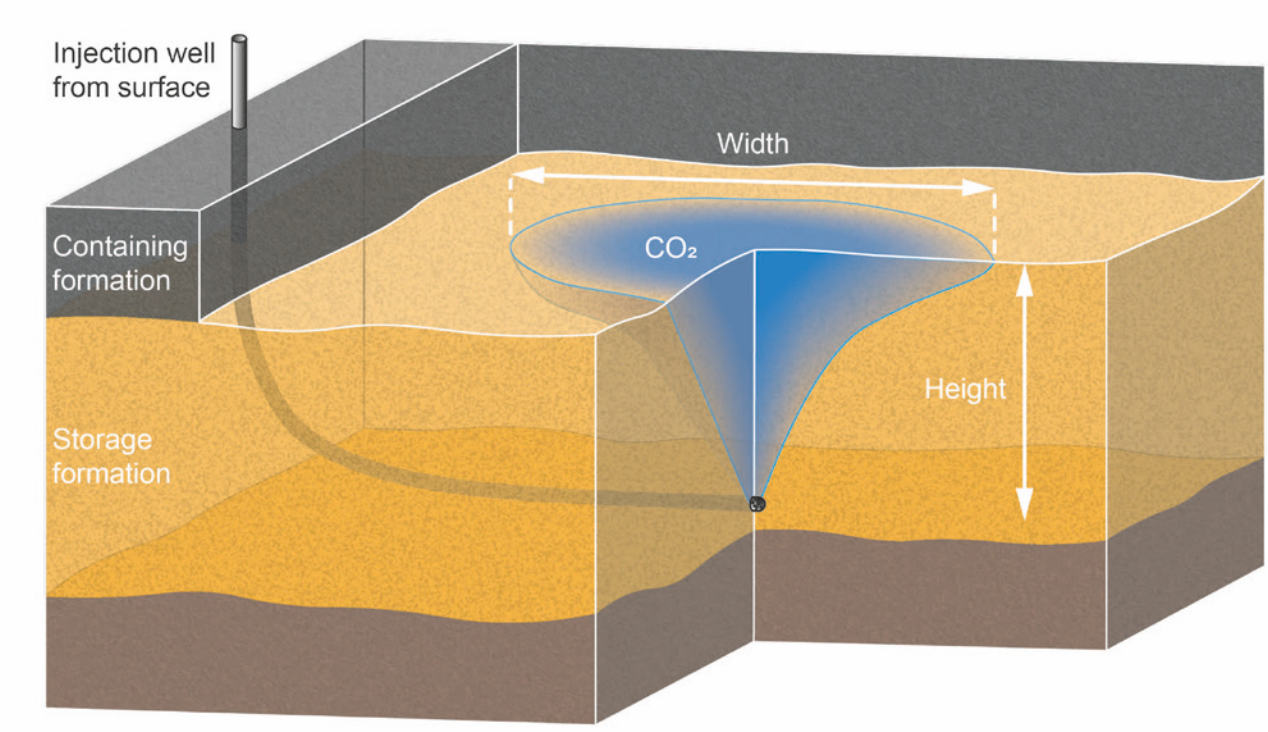

Figure 7 An example diagrammatic illustration of computer modelling to predict the subsurface width and height of injected CO_2 and extent of monitoring at a UK storage research facility to address the science case. The black circle marks the CO_2 injection point. Sarah Hannis © BGS 2022.

monitoring surveys once injection had started, or whether it would also require a baseline survey before commencement of injection.

Conclusions from the CO_2 injection simulations

The subsurface dimensions of CO_2 injected at depths greater than 800 m using an ensemble of 21 models predicted a width of 70–400 m, with a mid-value of 160 m, and a height of 30–220 m, with a mid-value of 82 m. These values provided the stakeholder community with the likely requirements to monitor subsurface injection and containment at a research facility.

The results showed that a single seismic survey would not detect the presence of CO_2 in the majority of the models for all three of the injected volumes. However, CO_2 was detected in all models when compared to a pre-injection baseline survey. Modelling of the seismic response to the presence of CO_2 highlights that a good quality, high resolution, pre-injection, baseline seismic survey is needed to ensure detection of the three injected volumes tested if seismic survey is the preferred method to detect and monitor injected CO_2 at a research facility. The results also show that the greater the volume of CO_2 is injected, the more likely it is to be detected by seismic survey monitoring.

Research facility infrastructure options

A CO_2 storage research facility has the potential to be a large research infrastructure in terms of ambition, scale and cost. As a publicly funded project, a rigorous assessment of the viability and benefits of the infrastructure will be completed, following the guidance detailed in the Government's Guide to Developing the Project Business Case (HM Treasury, 2018).

A longlist of research infrastructure options that will be assessed to form a shortlist has been identified.

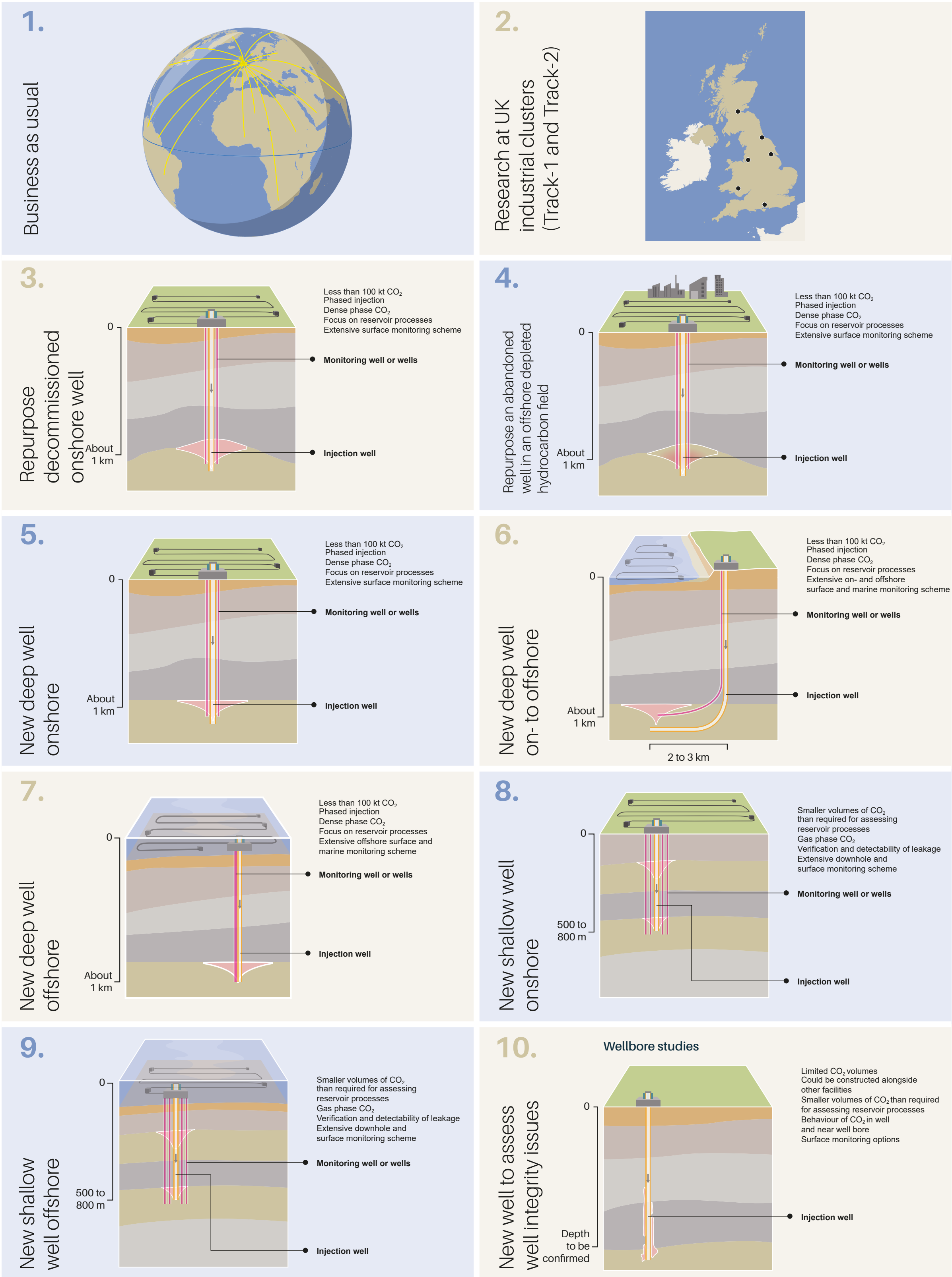

Figure 8 Longlist of CO_2 storage research facility infrastructure options. Units km: kilometre; m: metre; kt: kilotonnes. BGS © UKRI 2022.

The longlist and assessment criteria built on the input from the stakeholder engagement, were formed by BGS and NERC and ratified by the study steering committee. The longlist of infrastructure options is illustrated in Figure 8. Infrastructure at a facility may comprise combinations of the options. The science case, study objectives and a set of defined critical success factors will be used as criteria in the options assessment. The shortlist will be subject to a rigorous value-for-money appraisal in later stages of the project before a preferred way forward is identified.

7 Next steps to a CO_2 storage research facility

A full proposal for a second phase of scoping was submitted to the UKRI Infrastructure Fund in June 2021. If this proposal is successful, then an outline business case for a new infrastructure would be developed, based on this scoping study.

The second phase would further the programme by developing the design for, and completing a technical feasibility assessment of, a shortlist selected from the infrastructure options (Section 6.2). Partnerships, governance and operational models for the infrastructure would also be developed. Assuming a successful case is made and the outputs from the second phase continue to support the need for a facility, NERC would develop a funding bid to commission the infrastructure.

8 How to get involved

This study has conducted initial research and scoping for a proposed CO_2 storage research facility. A stakeholder engagement programme has been a key contribution to define the science case. It has also considered the societal background to CO_2 storage, public attitudes and understanding of the technology and support for its role in the UK's future.

Scoping studies for a UK deep geological CO_2 storage research facility remain in progress. A second phase of scoping is planned to support the development, delivery and operation for a CO_2 storage research facility. The success of the project will be dependent on engagement with the stakeholder community.

Enquiries from stakeholders and interested parties who wish to get involved with the scoping of a UK deep geological CO_2 storage research facility are welcomed. Such parties are encouraged to contact enquiries@bgs.ac.uk.

9 Glossary

Brine	Very salty water, i.e. water containing a high concentration of dissolved salts.
Borehole	See **well**.
CCUS	CO_2 capture, utilisation and storage.
CO_2	Carbon dioxide.
CO_2 injection well	A drilled hole through which CO_2 is transported underground into porous rock.
CO_2 storage capacity	The mass of CO_2 that can be contained in a geological store, calculated using average or accurate values. Accurate values are either obtained from hydrocarbon production or from computer simulations.
Containing formation	An impermeable layer of rock over a storage formation or hydrocarbon field that acts as a barrier to the movement of liquid and gas.
Dense-phase CO_2	At a temperature of more than 31°C and a pressure more than 7.4 MPa, CO_2 is a fluid that has the density of a liquid and behaves like a gas.
Gaseous-phase CO_2	At low temperature and pressure, such as room temperature and atmospheric pressure, CO_2 is a gas.
Geological CO_2 store	A body of rock or sediment that is sufficiently porous and permeable to host and store CO_2. Sandstone and limestone are the most common storage rocks. Rocks that contain hydrocarbons, known as an oil and gas field, can also store CO_2.
Geological formation	A body of rock with recognisable boundaries that is large enough to be represented on a geological map.
Infrastructure	The physical surface and subsurface structures needed to operate a facility.
Monitoring well	A drilled hole used to measure subsurface conditions, such as temperature and pressure.
Overburden	The geological strata lying between the containing formation and the seabed or ground surface.
Permeable	Allowing fluid to pass through.
Pore space	The volume of a rock that is not occupied by minerals. These gaps are called pores and they can be filled by various fluids; typically, in deep rocks, the fluid is salty water but it can also be oil or gases like methane or naturally formed CO_2.
Seismic survey	A method of investigating the subsurface using reflected sound waves.
Storage formation	A permeable and porous body of rock. Most geological formations at shallow depths contain fresh water used for human consumption. Formations at greater depth are filled with salty water that is unsuitable for any human needs. A storage formation may include a hydrocarbon field where they are known from the extraction of oil and gas.
Well (or borehole)	A circular hole made by drilling, especially a deep hole of a small diameter, such as an oil well.

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The British Geological Survey holds most of the references listed below and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://of-ukrinerc.olib.oclc.org/folio/.

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