CO_2 Storage Resources and their Development

An IEA CCUS Handbook

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Abstract

Carbon capture, utilisation and storage (CCUS) technologies are an important solution for the decarbonisation of the global energy system as it proceeds down the path to net zero emissions. CCUS can contribute to the decarbonisation of the industrial and power generation sectors, and can also unlock technology-based carbon dioxide (CO_2) removal. However, its successful deployment hinges on the availability of CO_2 storage. For widespread CCUS deployment to occur, CO_2 storage infrastructure needs to develop at the same speed or faster than CO_2 capture facilities.

CO_2 has been injected into the Earth's subsurface since the 1970s and dedicated CO_2 storage (where CO_2 is injected for the purpose of its storage and not for CO_2-based enhanced oil recovery) has been occurring since 1996. There are seven commercial-scale dedicated CO_2 storage sites today, with more than 100 others in development. Lessons learned from these sites, along with research, pilot and demonstration projects, contribute to our understanding of CO_2 storage resources, their assessment and their development into CO_2 storage sites.

This IEA CCUS Handbook is an aid for energy sector stakeholders on CO_2 storage resources and their development. It provides an overview of geological storage, its benefits, risks and socio-economic considerations. The handbook is supported by an extensive glossary of CO_2 storage-related terminology found at the end of this report and complements the IEA CCUS Handbook on Legal and Regulatory Frameworks.

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Executive summary

CO_2 storage enables net zero goals

CO_2 storage is a proven and effective way to permanently isolate captured CO_2 from the atmosphere. Currently, seven dedicated commercial-scale CO_2 storage sites inject around 10 Mt of CO_2 annually into deep geological formations. The piloting and demonstration of dedicated storage has been occurring since the 1990s. Dedicated storage also builds upon 50 years of lessons learned from CO_2 enhanced oil recovery (CO_2-EOR) and over 150 years of subsurface activity by the oil and gas sector.

Access to safe and secure geological CO_2 storage is critical to CO_2 management in the context of stabilising global temperature rise. In the IEA's Net Zero Emissions by 2050 Scenario, 5.9 Gt of captured CO_2 is stored annually in 2050. Enterprises may be hesitant to invest in CO_2 capture if they are not confident that CO_2 storage will be available to store captured emissions. Global CO_2 storage development is currently lagging behind the development of CO_2 capture. Targeted government intervention and expanding policy support to encompass CO_2 storage development can help accelerate its progress.

Technology-based CO_2 removal requires CO_2 storage. Direct air capture with CO_2 storage (DACS) and bioenergy with carbon capture and storage (BECCS) rely on geological storage to permanently remove captured CO_2. Without CO_2 storage, the potential for carbon removal offered by these technologies cannot be realised.

Resource assessment and development take time, but momentum is building

As of the middle of 2022, more than 130 CO_2 storage sites are in development in 20 countries. Many of these sites have been in development for years, but plans for 60 new storage projects were announced in 2021. By 2030 annual dedicated injection capacity could increase to more than 110 Mt from some 10 Mt today.

Ample CO_2 storage resources may be available globally, but further assessment is required. Globally, CO_2 storage resources are under-appraised and only a small handful qualify as reserves that can be developed into sites. To support the development of resource management strategies, governments should assess CO_2 storage potential and define reserves. It can take three to ten years to develop suitable resources into operating sites and not every resource will be developable. Government-led precompetitive resource assessment can reduce the financial risks of developing CO_2 storage and accelerate the creation of new sites.

Phasing the assessment and development process is efficient and effective. Assessment becomes increasingly detailed and costly as it proceeds. A phased process allows resources that do not meet project criteria to be excluded from further assessment. This reduces exploration risk and increases confidence in storage. Phasing also allows different actors to conduct different phases of assessment so, for example, the private sector can build on precompetitive assessments conducted by governments.

Storage-related risks are manageable

The technical risks associated with CO_2 storage can be managed effectively. Regulatory oversight, robust site assessment and competent site operations support risk management and contribute to CO_2 storage security. Measurement, monitoring and verification (MMV) programmes – a mandatory part of CO_2 storage operations – underpin risk management processes and demonstrate effective CO_2 storage. To date, pilot, demonstration and commercial CO_2 storage projects have supported the development of MMV expertise and experience. Regulators should ensure that frameworks outline MMV requirements without being overly prescriptive as to the types of technologies that need to be used.

Business model development will support economic risk reduction. New business models are emerging as dedicated CO_2 storage activity increases to support decarbonisation efforts. Business models from other sectors can provide guidance, but regionally informed, storage-specific business models are needed to support upscaling and widespread deployment. Such models have to account for the unique market and financial risks faced by the developing storage industry, be guided by local policies and regulation, and address risk sharing, long-term liability and revenue models. Since CO_2 storage sites are effectively providing a public service, both the public and private sectors should play a role in developing sustainable business models for CO_2 storage activity.

Commercialisation requires policy support

Developing large, multi-source CO_2 storage sites should be a top priority. Multi-source storage sites are the foundation of a hub model for deploying CO_2 storage. They capitalise on economies of scale to reduce storage costs and support the deployment of CO_2 capture at emitters where full-chain CCUS projects are not feasible, such as emitters that are small or have no storage expertise.

CO_2 storage costs may increase with time due to resource availability and quality. Resources that have the most data, are the most accessible or are the largest or least complex are likely to be developed first. As a result, assessment, development, operating and monitoring costs may increase due to the need to gather additional data, or due to increased complexity of injection operations, or both. Learning-related cost reductions can offset cost increases, while resource management can support the strategic development of resources, which can in turn reduce disruptive cost increases.

Decarbonisation strategies should account for the location of storage resources. CO_2 storage resources are immovable, so the benefits of siting new facilities that will capture CO_2 alongside CO_2 storage resources should be considered. Through economies of agglomeration, this could support CO_2 storage hub development, CO_2 transport cost reductions, and the strategic development of DACS and BECCS facilities in regions with both storage resources and high potential for renewable energy or bioenergy feedstock.

Getting started on CO_2 storage resource assessment

Many industrial and power generation facilities in emerging market and developing economies (EMDEs) are relatively young, increasing the case for CCUS deployment in these countries in particular. Some of these countries have started to assess their CO_2 storage resources, but many have not. The IEA has devised the following checklist for governments that are interested in developing an atlas or database of their CO_2 storage resources. It predominantly targets EMDEs, but can be used by any country or region as a starting point. Not every step will be required or relevant to every country or region.

1. **National CCUS focal point**

- Assess whether CO_2 storage resources fall under the mandate of any agency or agencies.
- Identify and nominate an organisation or agency to serve as a national CCUS focal point.
- Consider engaging the national geological survey or equivalent.

2. **International support**

- Consider engaging international expertise and support to assist with the process, such as the IEA, IEAGHG and World Bank.

3. **CO_2 storage assessment project team**

- Determine which agency should co-ordinate/be involved in the resource assessment process.
- Define a project team to reanalyse existing geological data with the goal of identifying CO_2 storage resources.
- Decide which internationally recognised storage assessment methodology should be used.

4. **Leverage national human capacity**

- Initiate discussion on CO_2 storage with stakeholders who may be able to assist in the assessment process, such as oil and gas companies, local universities and research centres with subsurface expertise, and other government agencies.

5. **Data**

- Identify owners and custodians of geological data, which may be government agencies, private-sector companies, research organisations, etc.
- Gather as much existing relevant geological data as possible and make it publicly available whenever possible.

6. **CO_2 storage assessment**

- Assess the collated data. As a part of assessment, clearly define the methodology and assumptions that were used.
- Make assessment results publicly available whenever possible.

7. **Next steps**

- Determine if there are specific resources that should be targeted at further assessment.
- Outline priorities for future CO_2 storage-related work and consider defining a CCUS deployment work programme.

Priority actions to develop CO_2 storage resources

To reduce the risk of CO_2 storage becoming a bottleneck during energy transitions, the IEA has identified five categories of priority actions that governments can take to accelerate CO_2 storage development. The private sector can support these actions through consultation during the development of policies and regulation, improving data management practices, increasing innovation, and supporting the upskilling and reskilling of the oil and gas workforce. Additionally, the IEA has defined specific considerations for the private sector to support CO_2 storage deployment.

Identify CO_2 storage resources and facilitate access to the data necessary for storage development

- Develop national CO_2 storage resource atlases or databases using internationally agreed methodology, such as the Storage Resource Management System (SRMS), and existing subsurface data.
- Accelerate pre-commercial exploration for CO_2 storage in order to increase confidence in storage resource availability and performance.
- Support countries and regions without storage experience by encouraging knowledge transfer and data sharing.
- Improve data management, support digitisation of legacy records, and ensure data are accessible.

Ensure legal and regulatory frameworks enable effective and secure CO_2 storage

- Outline characterisation, quantification and MMV requirements in regulatory frameworks.
- Address CO_2 storage-specific liabilities.
- Define clear licensing and permitting processes and appropriately staff agencies to support efficient and timely permit issuing.
- Clearly define the ownership of, access to and management of subsurface pore space if it is not already defined.
- Consider the ownership of new subsurface data and if newly acquired subsurface data should be considered a public good after a set period of time.

Develop policies and regulatory competencies that support CO_2 storage

- Determine if CO_2 storage, and by extension CCUS, should be integrated into national climate, energy, industrial and decarbonisation strategies. If yes, develop an appropriate resource management plan.
- Implement policies to encourage CO_2 storage investment, such as direct incentives or market-based policies like a carbon tax, takeback obligation or emissions trading system.
- Define methods of risk allocation and/or risk sharing between public and private sectors.

- Incentivise the development of CO_2 transport and storage hubs to support the decarbonisation of industrial clusters and encourage the co-location of clean energy technologies with CO_2 storage resources.
- Foster public support by developing robust communication channels and allowing for public engagement opportunities.

Support early movers, develop business models and boost investment in CO_2 storage

- Develop dedicated incentives to support resource assessment and development.
- Provide early movers with access to targeted funding that is contingent on active resource assessment and knowledge/data sharing. For example, an exploration tax credit could encourage companies to perform resource assessments.
- Encourage public–private partnerships on storage development.
- Ensure ongoing development funding to support CCUS and storage development.

Support the development of CO_2 storage competencies, expertise and technologies

- Engage in or support technology development that can improve resource assessment, site operations and MMV processes.
- Support the reskilling and upskilling of oil and gas workforces so they are also able to work on CO_2 storage.
- Encourage the development of CO_2 storage and CCUS research, engineering and technology programmes at the university level and at national research centres.
- Incentivise private-sector companies with CCUS experience to invest in the national workforce, in the form of training and apprenticeships, to truly build on the human capacity needed to deploy projects.
- Develop technology solutions that enable the co-location of different clean energy technology solutions.

Private-sector considerations

- Consider creating a market for tradeable, regulatory compliant CO_2 storage certificates.
- Incorporate CO_2 management into corporate decarbonisation and environmental, sustainability and governance (ESG) strategies. As part of this, consider if CCUS should be included in current and future growth strategies.
- Develop and build CO_2 storage infrastructure.[1]
- Drive investment towards CO_2 storage infrastructure by supporting CO_2 management and insuring it is permissible within sustainable finance metrics.
- Create insurance products that cover CO_2 storage activities.
- Recognise proven CO_2 storage reserves as an asset.[2]

[1] This can also be done by state-owned enterprises and public–private partnerships.

[2] The Storage Resource Management System published by the Society of Petroleum Engineers provides a mechanism to assign a book value to CO_2 storage resources.

Introduction

Context of this IEA CCUS Handbook on CO_2 storage

Carbon capture, utilisation and storage (CCUS) technologies provide significant decarbonisation potential and their widespread deployment is an integral part of a lower-cost and more attainable net zero future. In the IEA Net Zero Emissions by 2050 Scenario (Net Zero Scenario), some 5.9 Gt of CO_2 are captured and stored in 2050. This requires significant expansion of dedicated CO_2 storage capacity since today around 10 Mt of CO_2 is injected annually into dedicated CO_2 storage sites.

For CCUS technologies to achieve their CO_2 management potential, a significant and expedient scale-up of CO_2 storage from the megatonne to gigatonne scale is required. Access to effective and secure CO_2 storage enables widespread deployment of CO_2 capture technologies during energy transitions, making it the most pivotal component of the CO_2 management value chain. Without confidence in CO_2 storage availability, the decarbonisation potential of CCUS technologies is significantly reduced. Additionally, technology-based CO_2 removals – bioenergy with carbon capture and storage (BECCS) and direct air capture with storage (DACS) – require CO_2 storage.

A gap is developing between ambitions to develop CO_2 capture and ambitions to develop CO_2 storage. Without urgent and concerted action by the public and private sectors to accelerate CO_2 storage assessment and development, this gap may continue to grow, risking negative final investment decisions (FIDs) on capture facilities or inefficient investment.

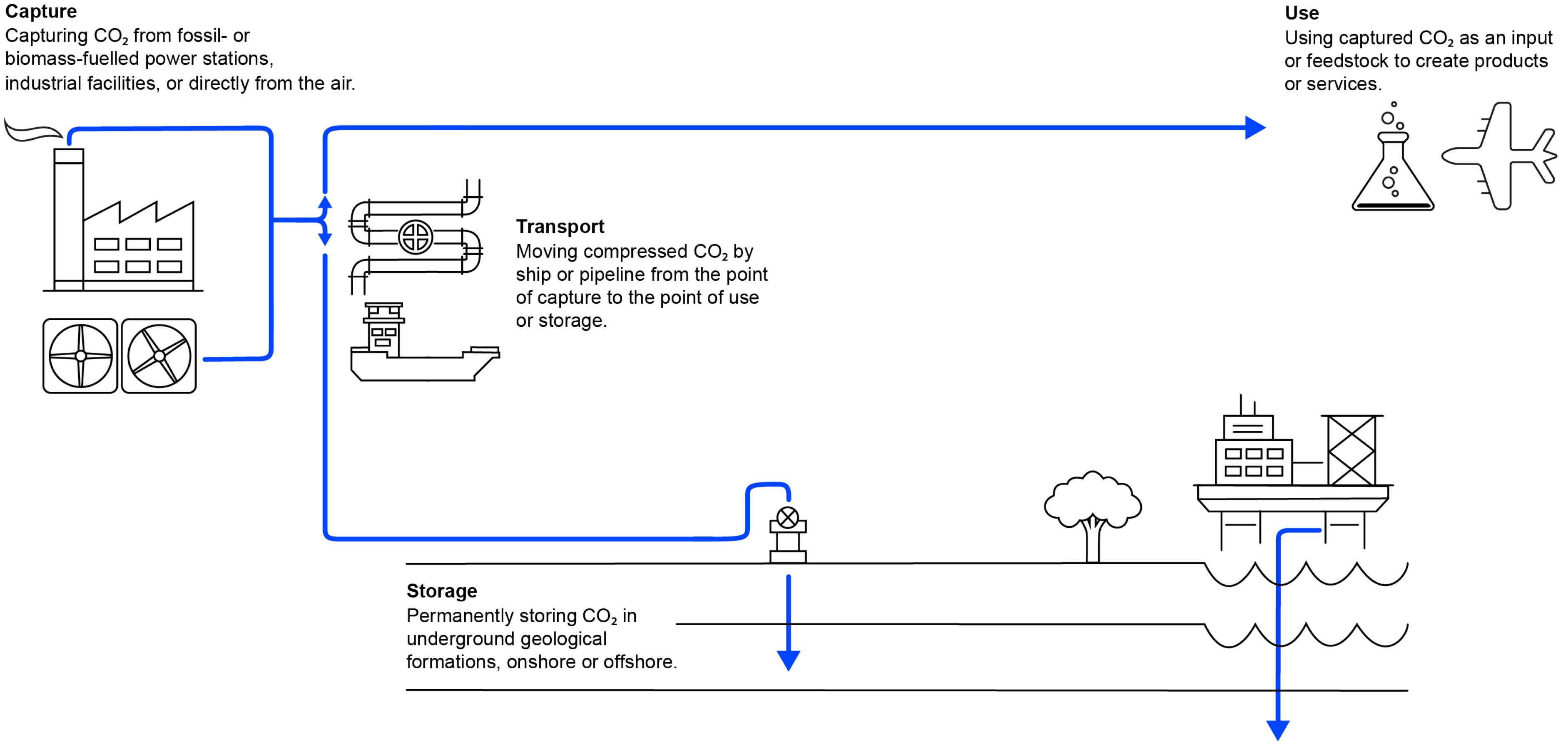
To deploy CO_2 storage on a gigatonne scale, storage resources need to be assessed and developed, storage activities need to be regulated, a market for CO_2 storage needs to be built, and policy needs to be designed to support this. The energy sector should consider the role CO_2 storage will play in its decarbonisation. Storage deployment can be supported by stakeholders across the energy sector and both the public and private sectors can play a role. To that end, the IEA has identified several major technical, economic, policy, and legal and regulatory considerations that feed into the deployment of CO_2 storage infrastructure.

Info point: About the IEA CCUS Handbook series

Meeting net zero goals will require a rapid scale-up of CCUS globally, from tens of millions of tonnes of CO_2 captured today to billions of tonnes by 2030 and beyond.

The IEA CCUS Handbook series aims to support the accelerated development and deployment of CCUS by sharing global good practice and experience. The handbooks provide a practical resource for policy makers and stakeholders across the energy industry to navigate a range of technical, economic, policy, legal and social issues for CCUS implementation.

Schematic of a potential CO_2 management value chain



Note: CO_2 transport can also include barges, trains and tank trucks.

Structure of this handbook

This IEA CCUS Handbook aims to be a resource on CO_2 storage that can be used by stakeholders across the energy industry to better understand CO_2 storage, from resource assessment onwards.

The handbook is structured as follows:

Chapter 1. Introduction outlines the structure of this handbook and introduces the importance of CO_2 storage in energy transitions.

Chapter 2. CO_2 storage resources provides a general introduction to what CO_2 storage resources are, how much CO_2 can be injected and how it is trapped in a geological formation.

Chapter 3. CO_2 storage projects presents the lifecycle of a CO_2 storage project, the skills and competencies that support CO_2 storage projects, and frameworks that can be used to develop projects.

Chapter 4. Assessment and development breaks down the resource assessment and development process into its component phases and defines key considerations for each phase.

Chapter 5. Technical assessment criteria goes through the four main technical criteria that are evaluated during resource assessment and development.

Chapter 6. Risk management outlines the role risk management has in CO_2 storage activities. It goes through the main risk management processes.

Chapter 7. Technical risks provides an overview of the five main categories of technical risks that must be managed by a CO_2 storage project.

Chapter 8. Commercialisation of CO_2 storage addresses the socio-economic aspects of CO_2 storage projects, including business models and long-term liability.

Chapter 9. Actions to support deployment looks at how CO_2 storage deployment can be accelerated and provides concrete actions that can be taken by policy makers and the private sector.

The handbook is supported by an extensive glossary of CO_2 storage-related terminology found at the end of this report. It complements the IEA CCUS Handbook on Legal and Regulatory Frameworks.

CO_2 storage resources

Chapter summary

CO_2 storage resources are porous subsurface rocks that can trap injected CO_2. They can be broadly divided into three types: saline formations (or saline aquifers), depleted oil and gas fields, and unconventional resources (igneous rocks, unmineable coal seams and organic shales). Storage resources can be found globally, but like other natural resources they are not evenly distributed.

How much CO_2 can be injected will depend on the physical properties of the resource along with site engineering and regulation (see Chapter 5 for more detailed discussion).

Once injected, CO_2 becomes trapped by physical and chemical processes allowing it to remain safely stored for thousands of years. The four main mechanisms – structural/stratigraphic, residual, solubility/dissolution, and mineral trapping – occur on different timescales and at different ratios depending on reservoir characteristics and injection type.

Policy actions:

- Determine the type of storage resources available in a region or country.
- Assess CO_2 storage resources on a national or regional level.
- Identify countries and regions where storage resources are likely to be present, but have not been assessed.
- Support storage resource assessments in emerging market and developing economies.

CO_2 storage is an effective and secure way to permanently isolate emissions

Geological storage involves injecting captured CO_2 deep into the subsurface where it is trapped. Since the 1970s CO_2 has been injected into the subsurface for the purpose of enhanced oil recovery (EOR). In 1996 the first dedicated CO_2 storage project (i.e. not using the CO_2 for EOR, but to reduce emissions) was commissioned at the Sleipner gas fields in Norway. Decades of safe CO_2 injection into the subsurface and more than 150 years of subsurface activity, engineering and innovation support the wide deployment of CO_2 storage.

Like oil and natural gas, CO_2 deposits can be found in the subsurface. The Bravo Dome CO_2 gas field in the United States is one such example, where natural processes have trapped CO_2 for over 1 million years. These same natural processes can be exploited to trap and immobilise injected CO_2. This is the foundation of geological CO_2 storage. In appropriately characterised, developed and operated storage sites, CO_2 can be expected to remain trapped permanently.

A place where fluid or gas collects in the subsurface is known as a reservoir. Reservoirs are permeable and porous rock formations found deep underground both on and offshore. When reservoirs are found in proximity to one another the resulting area is called a field.

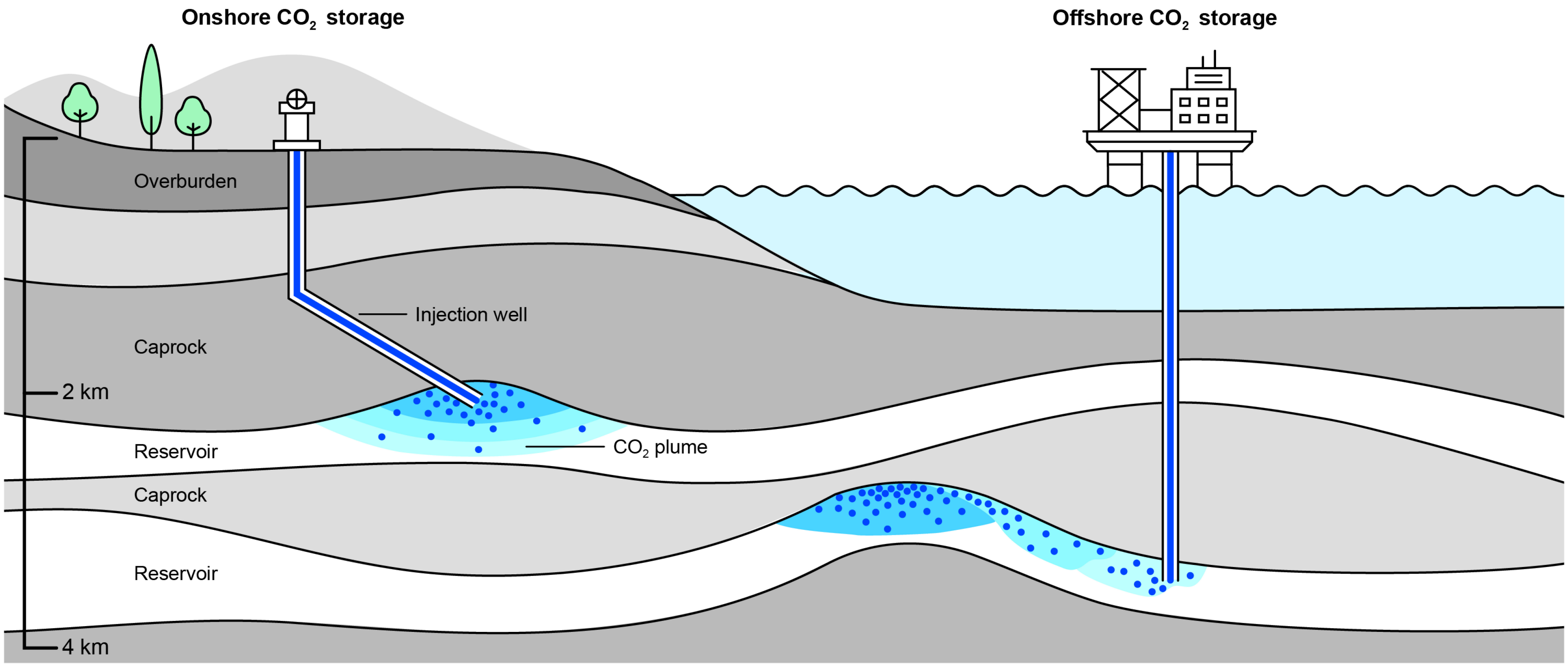
Reservoirs can contain oil and gas, naturally occurring CO_2, freshwater, saltwater (commonly called brine) and other fluids. Reservoirs suitable for geological storage of CO_2 are found in sedimentary basins – regions where accumulated sediment has been compacted into rock. However, some igneous rock formations may also be suitable for CO_2 storage.[3] In order to contain CO_2, reservoirs generally should be capped by an impermeable layer of rock known as a caprock or seal. These seals directly contribute to storage security and should have sufficient lateral extent that CO_2 cannot spread beyond their boundaries and migrate to the surface.

During the storage process, CO_2 is injected into a suitable geological reservoir where it will remain trapped in a defined area. For injection to be successful, CO_2 needs to be at a slightly higher pressure than the targeted reservoir. Typically, CO_2 is injected in its dense phase at high pressure (> 100 bar) to depths below 800 m, where subsurface pressure allows the CO_2 to remain in its densest and most compressed phase. Inside the reservoir, CO_2 often becomes a supercritical fluid – dense like a liquid, but with low viscosity like a gas – as it warms to reservoir temperature and remains under high pressure. This allows for the efficient use of storage space.

[3] Storage in basalts, a type of igneous rock, has been piloted in Iceland and the United States; however, additional demonstration is needed to ascertain the viability of widespread deployment and scale-up of this type of storage.

Where CO_2 is injected

Schematic of onshore and offshore CO_2 storage reservoirs



Note: As with oil and gas wells, CO_2 injection wells can be vertical, horizontal or deviated.

Types of CO_2 storage resources

CO_2 storage resources are permeable rock formations with pores – small holes and voids between mineral grains – that can be filled with CO_2. These resources can be divided into three main categories: saline formations, depleted oil and gas fields (areas with one or more reservoirs), and unconventional storage resources.

Saline formations

Saline formations, also known as saline aquifers, are porous and permeable sedimentary rocks that contain salty, non-potable water commonly known as brine. They are a common geological feature with wide geographic distribution. Some 98% of the world's estimated CO_2 storage resources are in the form of saline aquifers and they offer significant theoretical storage capacity. However, on a global scale, the usable capacity of these resources is unknown because there is insufficient site-specific data to characterise them. To date – in the absence of a strong climate imperative – the lack of an economic driver means that the process of assessing these resources' potential has not substantially progressed. Typically, saline aquifers near to, or in the same geological unit as, oil and gas reservoirs are better characterised than greenfield saline aquifers since they benefit from data collected during oil and gas activities.

Examples of operating projects in saline aquifers include: Gorgon CCS in Australia, Quest CCUS in Canada, Illinois Industrial CCS in the United States and the Sleipner and Snøhvit projects in Norway.

Depleted oil and gas fields

Oil and gas fields are made up of one or more reservoirs where brine has been replaced by hydrocarbons. When it is no longer possible to extract hydrocarbons, a reservoir is considered depleted. While the processes and seals that trap hydrocarbons in oil and gas reservoirs can also trap CO_2, not every depleted reservoir will be suitable or available for CO_2 storage. In addition to technical considerations, many jurisdictions restrict CO_2 injection other than for the purpose of CO_2-EOR in fields where some reservoirs are still being used for hydrocarbon extraction, in order to minimise the risk of negative interactions between the resource and CO_2. In the near term, this could constrain the number of depleted oil and gas reservoirs available for dedicated CO_2 storage. Reservoirs with ongoing oil and gas extraction are not suitable for dedicated CO_2 storage, but they may be a target for CO_2-EOR or hybrid approaches.

Repurposing depleted oil and gas reservoirs into CO_2 storage sites offers several benefits. Due to extraction activities, these reservoirs usually have lower than natural reservoir pressure, are well characterised and have extensive existing infrastructure. Lower than natural reservoir pressure may make it easier to inject CO_2 into a reservoir, but needs to be evaluated on a site-by-site basis. Existing data can be reused, thereby reducing data acquisition costs. Existing infrastructure (platforms, wells, pumping stations, etc.) could potentially be reused or repurposed, leading to reduced decommissioning costs at the end of oil or gas extraction and reduced construction costs for the storage site. Existing infrastructure should be assessed to ensure that it is fit for purpose before a depleted reservoir is repurposed. As part of this, all legacy (i.e. pre-existing) wells will need to be assessed to ensure that they cannot become a pathway from which CO_2 could leak.

As of 2022, no dedicated CO_2 storage is occurring in depleted fields. However, a number of projects are in development, including the Acorn project and the HyNet North West storage site, both off the United Kingdom, Project Greensand off Denmark, Porthos and Aramis, both off the Netherlands, the offshore Bayu-Undan project in Timor-Leste, the Ravenna hub off Italy, and the Moomba CCS project in the Australian outback.

Unconventional storage resources

Basalts and **peridotites** are igneous rocks and are reactive to CO_2. When CO_2 is injected, some of the rock dissolves and chemical reactions convert a proportion of the injected CO_2 into solid minerals. Carbfix in Iceland operates the only active storage project in basalts and injected around 80 kt of CO_2 between 2014 and the middle of 2022. The company aims to expand operations with the Coda Terminal, a project that will inject 300 kt CO_2 per year starting in 2025. CO_2 storage in basalts was also piloted in the United States during the Wallula Basalt Sequestration Pilot Project.

Unmineable coal seams can absorb CO_2; however, methane is often released when CO_2 is injected into them. Ongoing research is examining how effectively these deposits can store CO_2.

Organic shales are a type of sedimentary rock rich in organic matter. Organic matter can absorb CO_2 in a manner similar to coal. Limited work has been done to date on the technical and economic feasibility of using these resources for storage.

Info point: CO_2 use for the extraction of oil, gas and water

CO_2 can be used as a working fluid in many underground applications, including for enhanced oil recovery (EOR), enhanced gas recovery (EGR), and enhanced water recovery (EWR). The primary objective of CO_2 injection in these applications is to enhance extraction. As a by-product, some CO_2 remains trapped in the subsurface. In the case of CO_2-EOR, over the lifetime of the project a significant proportion of the injected CO_2 is retained underground. CO_2-EOR can be optimised for CO_2 storage, also known as CO_2-EOR+. At least four additional activities to occur for conventional EOR operations to qualify. These include:

- Additional site characterisation and risk assessment to evaluate the storage capability of a site.
- Additional monitoring of vented and fugitive emissions.
- Additional subsurface monitoring.
- Changes to field abandonment practices.

Physical properties that influence CO_2 injection

Three physical properties – permeability, pressure and porosity – influence how much CO_2 can be injected into a reservoir, at what rate and for how long.

Permeability measures how easily a fluid can pass through a rock. While related to porosity, permeability is influenced by how pores are shaped and connected. It can either be measured directly or estimated during well logging. Dynamic flow tests with water or CO_2 are the most accurate way to assess reservoir permeability for CO_2 storage. **Relative permeability** quantifies how injected CO_2 and reservoir fluids interfere with one another as they both move through the reservoir. It measures the ability of two or more fluids to pass through a rock and can be measured in a lab, modelled using simulations or calculated from field performance data.

Pressure controls how easily CO_2 can be injected and how much CO_2 can be safely stored. **Reservoir pressure** is the pressure of fluid within the pores of the reservoir. It can be measured using bottom-hole pressure gauges and during well tests. Reservoir pressure changes with subsurface activity. Extraction removes fluids and usually causes pressure to decrease. Injection adds fluids and usually causes pressure to increase. **Fracture pressure** is the pressure required to fracture a reservoir or its seal. It can be calculated or modelled. CO_2 injections should not bring the reservoir above its fracture pressure or the fracture pressure of its seal.

Porosity is the volume of rock pores as a proportion of the total rock volume. Porosity can be measured directly from core samples or it can be derived during well logging – the process of recording the geological and geophysical characteristics of a well.

CO_2 is injected into a reservoir via a well at a pressure higher than that of the fluids within the target rock formation. Once CO_2 is injected, it forms a plume that migrates through the reservoir, pushing pre-existing reservoir fluids away from the injection zone. The CO_2 migrates within a network of interconnected pores where it mixes with or displaces pre-existing reservoir fluids. Fluid displacement and CO_2 injection cause pressure to build within the reservoir. Elevated pressure from around the injection zone will disperse through the reservoir and potentially into surrounding rock formations, travelling faster and further than the CO_2 plume or displaced fluids. In certain cases, increased subsurface pressure might be observed more than 100 km from the injection zone. Pressure build-up is an expected part of large-scale operations, and different techniques have been developed to manage it.

The volume of CO_2 that can be stored is determined by the pressure limits of a reservoir and how reservoir pressure responds to injection, as influenced by its porosity and permeability. A high-quality reservoir can have a porosity of 25% or more, be very permeable and be at or below its natural – hydrostatic – pressure.

Mechanisms that trap injected CO_2

Four main mechanisms trap CO_2 inside a reservoir. Each contributes to storage site performance and long-term security. They occur over different timescales and at different ratios depending on reservoir characteristics and injection type. CO_2 can be injected directly (as a gas, liquid or in supercritical form) or it can be injected in dissolved form. Each provides a different level of long-term security and immobilisation.

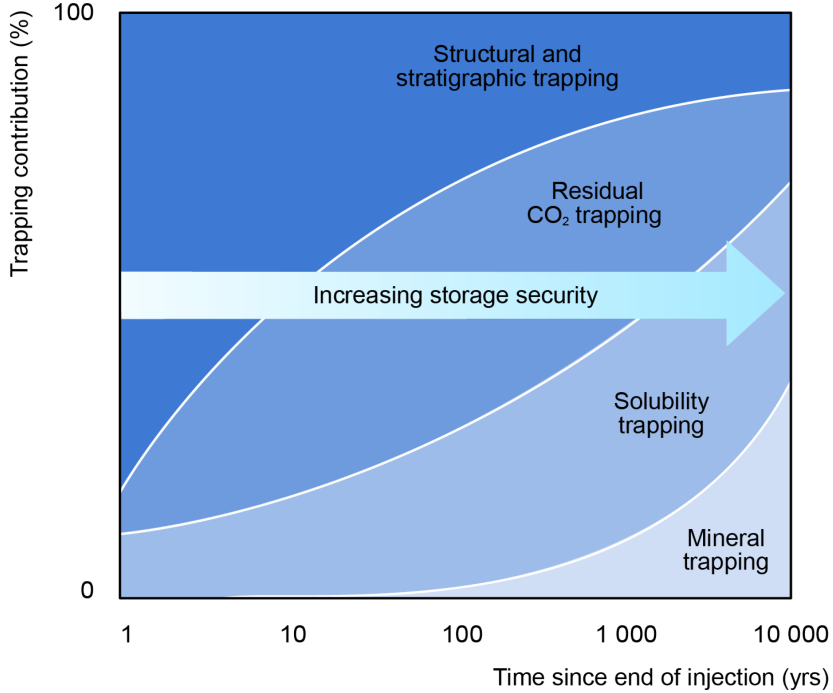
Structural or stratigraphic trapping is an immediate mechanism, trapping CO_2 in a reservoir via an impermeable upper boundary or caprock. Since CO_2 is usually less dense than reservoir fluids, it rises through the reservoir after injection. It stops once it reaches an impermeable boundary where it then spreads laterally. Its security is a function of the security of the seal. Seal penetration via wells or geological features (e.g. faults) could contribute to leakage risk.

Residual trapping can occur as the CO_2 plume moves through reservoir and displaces formation fluids. It is the trapping of CO_2 in small pores by physical forces (capillary action). This mechanism contributes to the long-term security of injected CO_2 and is a trapping mechanism that continues to work even if a seal fails.

Dissolution or solubility trapping occurs when CO_2 dissolves into formation fluids causing it to be trapped by geochemical means. CO_2-enriched formation fluids are denser than those that are non-enriched and over time they slowly sink through the formation until they reach an impermeable layer.

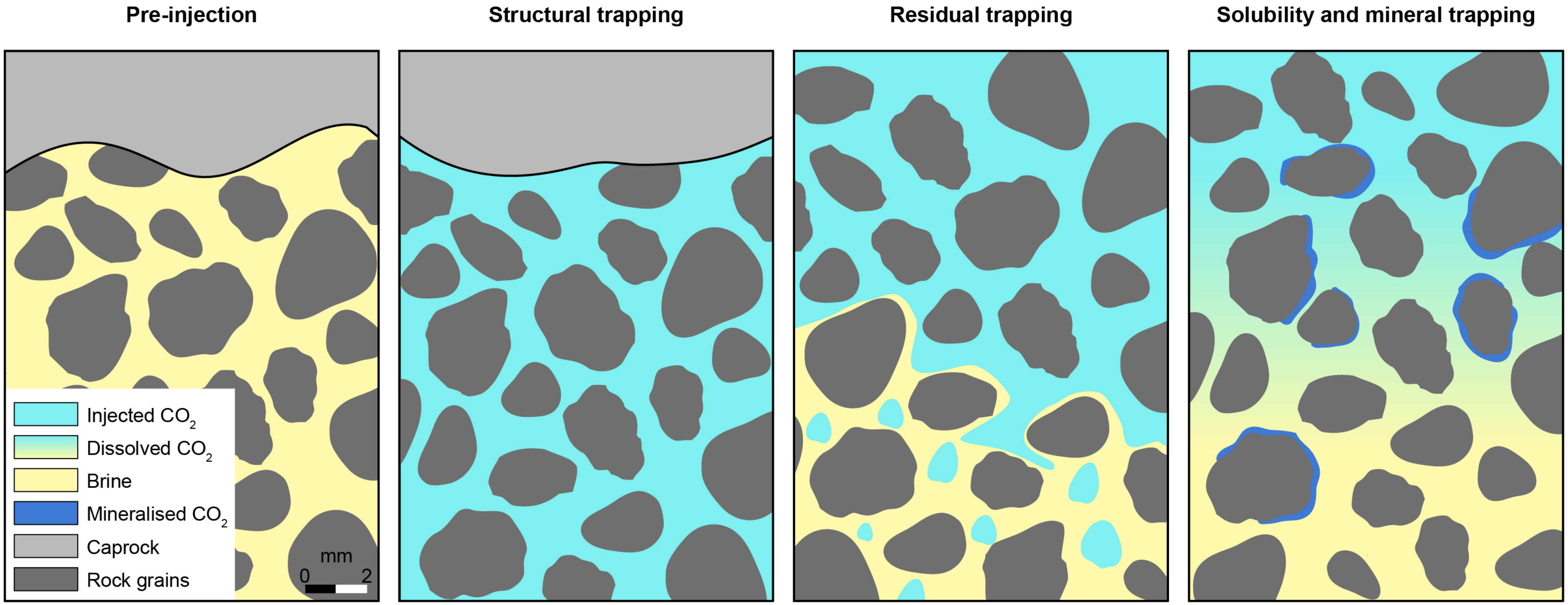
Mineral trapping occurs when dissolved CO_2 reacts with minerals in the reservoir to form solid carbonate minerals. This trapping mechanism stores CO_2 by incorporating it chemically into minerals. Depending on injection parameters and resource type, mineral trapping occurs on timescales ranging from minutes to millennia.

CO_2 trapping mechanisms and storage security



Source: Reproduced from Figure 5.9 in S. Benson et al. (2005), Underground geological storage, in B. Metz et al. (eds.), *IPCC Special Report on Carbon Dioxide Capture and Storage, Prepared by Working Group III of the IPCC*, Cambridge University Press, Cambridge, United Kingdom and New York, NY.

CO_2 trapping within a reservoir on a microscopic scale



Note: The scale and distance between mineral grains will vary between reservoirs.
Source: Adapted from S. Flude and J. Alcade (2020), Carbon capture and storage has stalled needlessly – three reasons why fears of CO_2 leakage are overblown, The Conversation (accessed 16 May 2022).

CO_2 storage projects

Chapter summary

CO_2 storage resources are a finite and strategic resource that countries should consider as they look to CO_2 management to support their decarbonisation strategies and energy transitions.

Like most large infrastructure projects, it takes time, experience and skills to develop CO_2 storage sites. Storage site development can take anywhere from about three years to more than ten depending on how well assessed the targeted storage resource is.

The lifecycle of a CO_2 storage site can be divided into six phases, each of which will require different levels of investment. Several resource assessment and development frameworks exist. Project developers should consider using the Storage Resource Management System (SRMS), which is based on the Petroleum Resource Management System (PRMS). The SRMS is project based and excludes certain types of storage resources, namely unconventional resources and those found in oil or gas fields with ongoing active extraction. The SRMS can be adapted to support assessments at a national or regional level, or assessments of resources that fall outside the framework. Alternatively, other frameworks can be used.

Source-sink matching can support the strategic roll-out of CO_2 storage sites and optimal resource development.

Policy actions:

- Consider the role CO_2 management and by extension CO_2 storage may have during regional or national energy transitions.
- Encourage the development of CO_2 storage-related expertise and competencies – this can include reskilling or upskilling the existing oil and gas labour pool.
- Determine if CO_2 storage resources should be considered strategic resources.
- Create a resource development plan and define synergies between existing natural resource development and CO_2 storage resource development.
- Use source-sink matching to identify links between existing emitting assets and CO_2 storage resources.
- Ensure regulation supports CO_2 storage development.

CO_2 storage resources are a strategic asset for energy transitions

Natural resources – such as water, minerals, energy resources and soil – underpin strategies for economic development and national security. Energy transitions require large-scale CO_2 management, underpinned by extensive CO_2 storage infrastructure. Since CO_2 storage resources are finite, non-renewable and support energy transitions, they represent a new type of economic resource. An argument can be made for storage resources to be considered strategic assets and for CO_2 storage sites to be considered critical infrastructure in the quest for net zero emissions.

Countries without an overview of their storage resources should consider their energy transition pathway and determine if it would be relevant to assess their CO_2 storage resources. Some countries and regions, mainly those with CCUS experience, have already performed initial precompetitive assessments.

Governments that decide to treat storage resources as a strategic natural resource should ensure that they are managed appropriately. This often includes creating a storage resources management plan, performing precompetitive resource assessments and supporting resource development through subsidies, knowledge sharing and other incentives. A defined process for issuing exploration licences and permitting storage sites is also needed. To support CO_2 storage development, governments may consider establishing preferential pathways for permitting, creating infrastructure development funds, or having state-owned enterprises manage storage assessment and site operations.

National storage assessments and CCUS deployment level

Country or region	National resource assessment level	CO_2 storage experience
Australia	▲	●
Brazil	▲	●
Canada	▲	●
People's Republic of China*	▲	●
European Union	▲	● to ●
Japan	▲	●
Korea	▲	●
Mexico	▲	●
Norway	▲	●
South Africa	▲	●
United Kingdom	▲	●
United States	▲	●

▲ = Assessed to effective capacity; ▲ = Assessed to theoretical capacity; ▲ = Moderately assessed; ● = At least one operating dedicated storage site; ● = At least one dedicated storage demonstration project; ● = Limited piloting experience or experience restricted to CO_2-EOR.

* Hereafter, "China".

Note: In the European Union CO_2 storage experience is country dependent.

Source: Based on IEA analysis and C. Consoli and N. Wildgust (2017).

The stages of a CO_2 storage project

	Resource assessment	Design and development	Construction	Operation	Closure	Post closure
Timeframe (year)	2-6	1-5	1-3	20-50	Variable	10+*
Investment level	Medium to high	Medium	High	Low	Moderate	Very low
SRMS category	Prospective	Contingent to capacity	Capacity	On injection	Stored	Stored
Description	Process to identify and study CO_2 storage resources. Investment carries exploration risk since not every resource will be developable.	Project planning and design including FEED activities and permitting in advance of FID.	Post-FID activities, including site construction, connection to transport lines, expansion of MMV instrumentation and drilling of additional wells.	Period of time during which CO_2 is actively injected into the subsurface. This is commonly referred to as "on injection".	Period between cessation of injection activities and the granting of a closure authorisation.	Period of time after injection ceases where the CO_2 plume is still actively being monitored. Time during which site responsibility is transferred if applicable.
Policy considerations	• Support resource assessment. • Create a management strategy for storage resources. • Define fit-for-purpose legal and regulatory frameworks. • Consider whether existing infrastructure nearing end of its life could be repurposed. • Ensure that resources are in place to support licensing and permitting. • Define safety criteria including MMV. • Outline site inspection requirements.		• Consider providing subsidies to support early movers. • Ensure regulatory framework allows for storage operations.		• Define well abandonment and surface remediation requirements. • Define the requirements for issuance of a closure certificate or equivalent. • Define length of time required for post-closure monitoring. Consider mechanism to transfer liability to the state after a period of post-closure monitoring.	

* Post-closure timeframes are jurisdictionally dependent and range from being unspecified to being over 50 years.

Notes: FEED = front-end engineering design; SRMS = Storage Resource Management System. Assessment and development activities carry exploration risk and assessed resources may be defined as undevelopable or not commercially viable. Investment needs are relative to overall costs.

Necessary expertise and competencies

Interdisciplinary teams will support CO_2 storage sites all the way from assessment through to post-closure monitoring. Teams will need to include subsurface experts – geoscientists, engineers and modellers – along with other specialists who have business, economic, risk, legal and regulatory, social and environmental assessment expertise. To support storage development, regulators will need to have the necessary regulatory and institutional capacity to allow for efficient licensing and permitting.

While there is significant overlap between the knowledge and expertise required for CO_2 storage and that used by the oil and gas industry, CO_2 storage requires certain specific expertise as well. Currently, CO_2 storage-specific expertise is limited globally, and therefore there is a strong need to develop it across disciplines. Specialists need, inter alia, the following knowledge and expertise:

- CO_2-specific well engineering, completion and injection technologies.
- Understanding and managing the reactivity and phases of CO_2 in a storage-specific context.
- CO_2 storage-related dynamic modelling.
- Environmental measurement, monitoring and verification.
- CO_2 containment and containment risk assessment.

To create a pipeline of future talent and support development of CO_2 storage competencies, university programmes related to petroleum geology or engineering could add modules related to CO_2 storage. Many universities are already renaming programmes and some are adding modules related to CO_2 storage (or CCUS).

Case study: Supporting the acquisition of CO_2 storage expertise

CO_2 storage-related knowledge and expertise can be developed through collaboration between government, industry, communities, educational organisations and other participants. This is especially relevant in regions with oil and gas activity, where the labour pool will already have many skills that support CO_2 storage and where employment may decline in the future due to a shift away from fossil fuels towards other sources of energy. Both HyNet NorthWest in the United Kingdom and Ravenna CCS in Italy are examples of CO_2 storage hubs in development that will support continued employment in regions facing imminent closure of upstream activities due to depleted reservoirs.

In addition to the private sector transitioning their workers from extraction to injection, postgraduate programmes such as Edinburgh's Carbon Management MSc, educational programmes such as the IEAGHG's Summer School and the US Department of Energy's Research Experience in Carbon Sequestration, and geoscience and engineering programmes at universities all support the acquisition of specific expertise and competencies.

Assessment and development frameworks

Existing national or regional storage resource atlases rarely share a common approach or classification framework, so it is usually not possible to compare resource availability between regions or countries. Depending on the methodology, the estimated volume of available storage resources can vary by two to five orders of magnitude for the same geological formation, and resource capacity is often reported as a range (refer to Chapter 5 for more information on how capacity is assessed). One study estimated that global capacity is between 8 000 Gt and 55 000 Gt. The quantification of CO_2 storage resources on all levels from local to global can be improved with better data, more detailed assessments focused on dynamic considerations, and a consistent classification methodology.

The assessment and development of storage resources need to comply with applicable local, regional and national regulations. They can be guided by international standards such as ISO TC 265 – 27914:2017,[4] best or recommended practices (e.g. DOE/NETL-2017/1844, DNVGL-RP-J203), or classification systems. Individual classification frameworks provide a common method that can be used to assess and categorise resources based on specific criteria. Those focused on primary resource identification (e.g. UN Framework Classification, CSLF Resources-Reserves Pyramid, US-DOE method, Boston square analysis) may be suitable for the development of national or regional atlases and databases. These approaches, at least initially, usually focus on the potential volume that can be stored rather than the rate and duration of CO_2 injection. While volume-based assessments are valuable for primary resource identification, they do not represent actual CO_2 storage capacity since injection rate and duration are more of a constraint than volume.

An internationally consistent approach to resource classification could help mature storage resource frameworks and support commercial investment. To that end, the Society of Petroleum Engineers (SPE) developed the Storage Resource Management System (SRMS). It is a project-specific approach that incorporates commercial and technical considerations. For saline aquifers and deleted oil or gas fields, it can be used to identify the size of a resource and how advanced a project is. It can also be adapted to other resource types. The SRMS functions in a similar manner to the Petroleum Resource Management System (PRMS) which is used by the petroleum industry. As a result, its methodology may be familiar to investors and lenders involved in hydrocarbon extraction and it can be used to assign a book value to a CO_2 storage resource, allowing it to be treated as an asset.

[4] ISO TC 265 – 27914:2017 is due to be revised in 2022. Readers should refer to the most up-to-date version of the standard.

Info point: The Storage Resource Management System

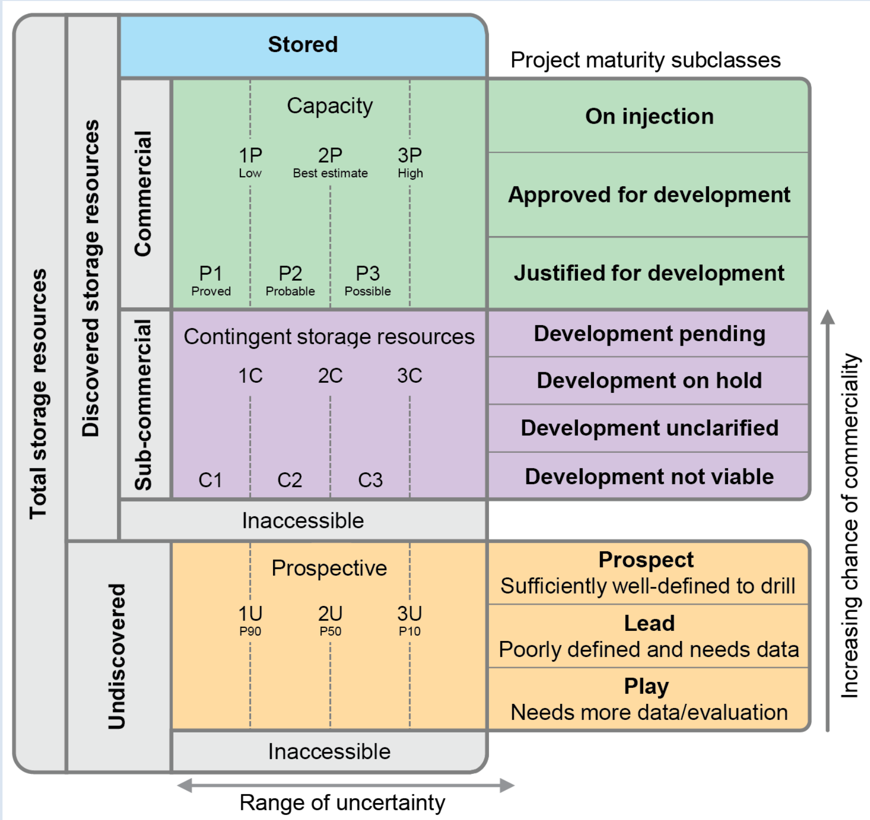
The SRMS was completed and adopted by SPE in 2017. The system is designed to classify CO_2 storage projects by their maturity and aims to provide a set of definitions that can be used internationally to compare projects and track progress on maturing storage resources.

The SRMS is project-based, with resources classified according to their commerciality and the level to which they have been assessed. If a resource that is being assessed is not clearly associated with a planned commercial project, the SRMS can still by applied by defining a nominal or theoretical project – in effect by identifying a technically and commercially realistic development concept.

As a resource moves up the classification framework, the chance that that project will develop into a commercial storage site increase. Similar to the PRMS, the SRMS includes a range of uncertainty in each class of project maturity. Uncertainty in the storable quantity of CO_2 increases from left to right.

Where the suitability for storage has not been determined for a specific subsurface storage formation, storage resources are classified as **Undiscovered**. Meanwhile, where the potential for storage within a specific subsurface formation has been quantified, storage resources are classified as **Discovered**. In both classes, resources can be defined as **Inaccessible** if they are not to be developed for storage at the current time. An example of an inaccessible resource would be one found in a jurisdiction where regulatory regimes prohibit storage. The prospective, contingent and capacity maturity classes can be further divided into subclasses.

The SRMS resource classification framework



Source: Reproduced with modifications from Society of Petroleum Engineers (2017), CO$_2$ Storage Resources Management System.

Case study: Applying the SRMS methodology globally

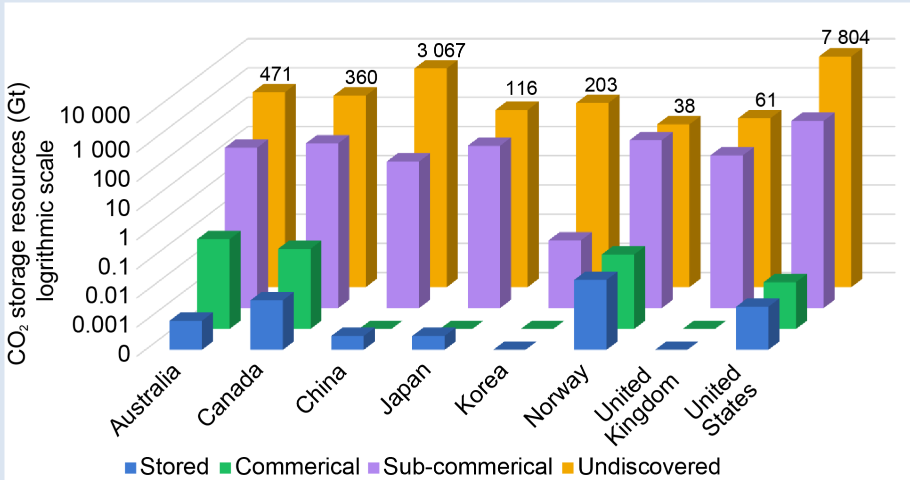
A Global CO_2 Storage Resource Catalogue, funded by the Oil and Gas Climate Initiative (OGCI), is being created over six 12-month cycles. During the process, existing data on CO_2 storage resources is reassessed using the SRMS methodology.

This work aims to provide a centralised publicly available database of CO_2 storage resources in key regions. It uses the SRMS methodology to compare resources across regions and to define the degree of global commercial readiness of CO_2 storage resources. In line with SRMS methodology, storage resources are classified as Undiscovered or Discovered based on technical and regulatory aspects. Only resources assessed by the SRMS methodology are included in the catalogue. Therefore, unconventional storage resources (such as basalts, coal seams and organic-rich shales), operating CO_2-EOR projects, and oil and gas reservoirs that are not fully depleted (with ongoing extraction activity) have been excluded.

At the end of the third assessment cycle, 852 sites had been assessed across 30 countries or regions. Nearly 14 000 Gt of storage resources were found across all SRMS maturity classes. More than 95% of those resources were classified as Undiscovered (Prospective) following the SRMS methodology. Only 96.6 Gt or 0.7% of resources assessed globally were part of defined projects. These results suggest that global storage potential is substantial. However, SRMS-classified commercial resources continue to be found only in four countries – Australia, Canada, Norway and the United States – which demonstrates the clear need for further resource assessment in order to identify global reserves. Those countries have regulatory and legal frameworks that allow for CO_2 storage, but still lack widespread investment and deployment.

The assessors also found that most storage resource assessments are not aligned with SRMS methodology and that it can be difficult to reassess resources with the SRMS methodology using only published information. For example, the resources associated with the Moomba project are not included in the catalogue even though Santos assigned them a book value in their 2021 reserves statement.

Storage catalogue results for selected countries



Source: Reproduced with modifications from OGCI (2022) CO_2 Storage Resource Catalogue.

Resource assessment and site development

The goal of the **resource assessment** process is to determine where, in what quantity, at what rate and for how long CO_2 can be injected. CO_2 storage projects generally have longer lead times than capture or transport due to substantial subsurface uncertainties and related study requirements. As a result, resource assessment needs to begin well in advance of capture project development. Countrywide assessment of CO_2 storage resources can take two to five years depending on the targeted level of detail and the amount of data collection required. It can take a further three to ten years to develop a CO_2 storage site from a countrywide or regional assessment. **Site development** is included in the resource assessment process and takes an assessed resource through permitting and the FID.

Governments can accelerate a region's level of storage readiness by conducting precompetitive resource assessments. As part of this, dedicated data acquisition programmes can include drilling, geochemical and hydrogeological studies, seismic campaigns and regional mapping. Depending on the level of detail, costs can be in the order of USD 10-100 million. Country or regional assessments may successfully end with the development of a resource atlas or a portfolio of resources earmarked for further assessment. Project-specific assessments will aim to develop one or more CO_2 storage sites. Resource assessment may end without identifying any commercially viable resources and capital expended during assessment activities carries exploration risk.

Case study: Financing storage assessments in emerging market and developing economies

National or regional assessment of CO_2 storage resources supports the deployment of CCUS. Storage resources have been assessed only in a limited number of emerging market and developing economies (EMDEs), mainly in Southeast Asia, and significant improvements can be made. Multilateral finance institutions have played a key role in supporting storage resource assessments in EMDEs.

The Asian Development Bank's CCS Fund is a multi-partner trust fund, established in 2009 and set to close in 2022. The fund has supported storage resource assessments, CCUS piloting and demonstration in Southeast Asia and the China.

The World Bank CCS Trust Fund, funded by the United Kingdom and Norway, was established in 2009 and is set to close in 2023. It has allocated more than USD 55 million to CCUS programmes in ten EMDEs, including support for high-level storage assessment and data input into storage atlases in Botswana, Egypt, Jordan, Mexico, Nigeria and South Africa.

Given that both of these trust funds are set to close in the near future, alternative ways to support CO_2 storage assessments in EMDEs are needed. Both banks are open to working with donor countries to develop new ways to support CCUS including CO_2 storage.

Case study: CCUS centres of excellence support storage development

CCUS centres of excellence, or their equivalent, can serve as a national focal point for CCUS research and development and contribute to the development of government strategies. This is especially valuable for EMDEs looking to deploy CCUS, since a centre of excellence can support this work.

The Indonesia Center for Excellence for CCS and CCUS is supported by the government's University Center of Excellences Program and the Ministry of Research, Technology and Higher Education. The centre was opened in 2017 and serves as a learning facility for CCUS. The centre aims to:

- Deliver a co-ordinated programme of CCUS research.
- Pilot CCUS in Indonesia and identify opportunities for CCUS deployment.
- Formulate policies, strategies and regulations that support implementation.
- Develop effective communication on CCUS.
- Provide educational and informational materials on CCUS.

The centre has led Indonesia's work on CCUS, including supporting the development of CCUS activities. In collaboration with industry and international partners it has created the Indonesia CO_2 Source–Sinks Mapping and Spatial Database and is conducting multiple CCUS-related feasibility studies.

Case study: Atlas on geological storage of carbon dioxide in South Africa

Since 2007, CCUS has been included in South Africa's long-term strategy for CO_2 emissions reduction. Given the country's energy mix, coal resources and coal-based petrochemical activities, CCUS technologies can allow for continued development while still decarbonising certain activities.

The first atlas on geological storage resources in South Africa was published in 2010. Prepared by the Council of Geosciences and the Petroleum Agency of South Africa, it covers depleted oil and gas reservoirs, unextractable coal seams and deep saline aquifers. The agencies used existing data from seismic surveys and historic drill cores to estimate the on and offshore storage potential of each resource type. Generally, there was higher confidence in offshore resource estimations due to the presence of significant data sets stemming from oil and gas activities.

The Atlas on Geological Storage of Carbon Dioxide in South Africa estimates the theoretical capacity of South Africa's storage resources to be around 150 Gt, with more than 98% of that capacity located offshore.

Subsequent assessment work has mainly focused on the Zululand, Algoa and Durban basins, and more recently on basalts in the Klipriversberg Group, where a pilot storage project is under development.

Source-sink matching

CO_2 storage resources are not evenly distributed globally. Desktop analysis can be used to estimate whether storage resources within a region are likely to be limited, sufficient or abundant in comparison with current and projected emissions. Following that, source-sink matching can be used to associate emission points (sources) with storage resources (sinks) based on a number of criteria. Source-sink matching exercises underpin the development of CO_2 storage resources in two main ways:

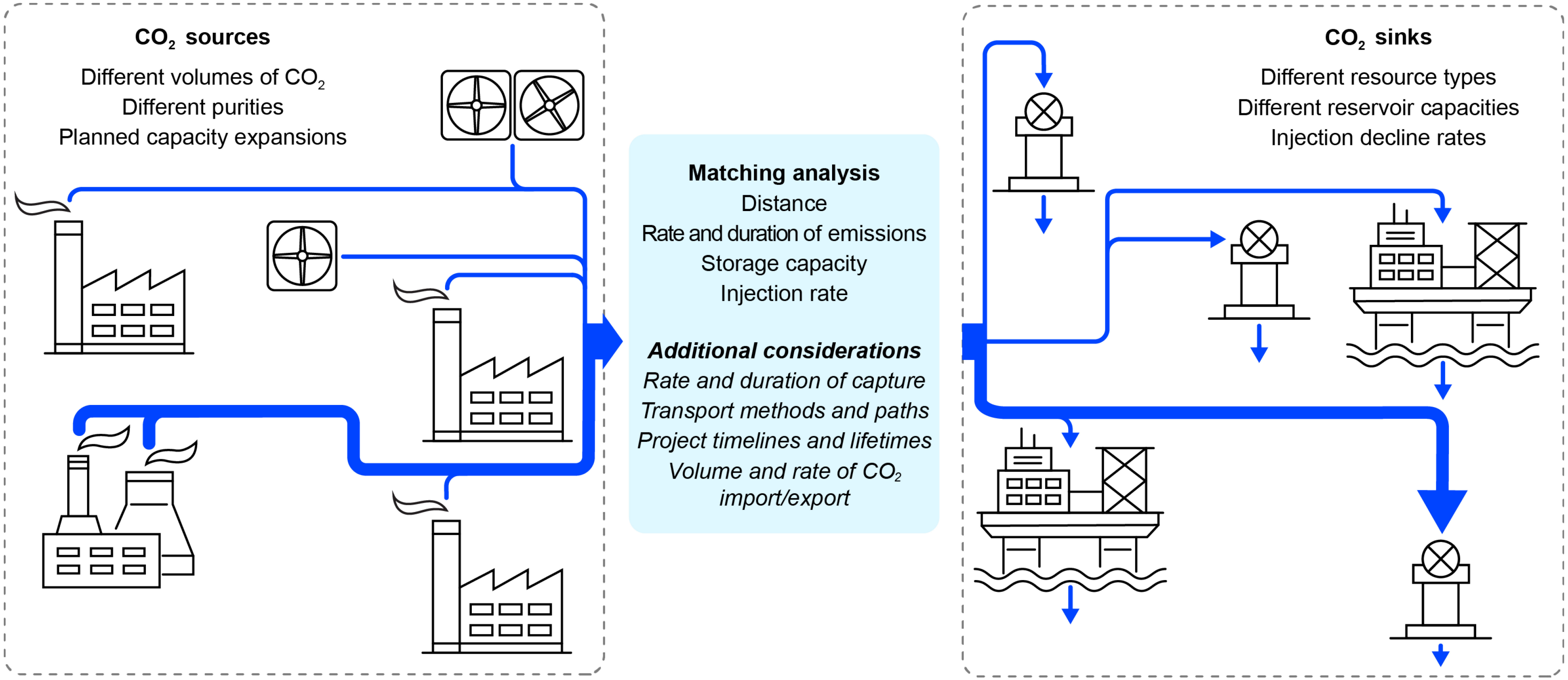
- From a policy perspective, they allow for the association of emission points with potential sinks as a precursor to assessing whether CO_2 storage resources within a region are sufficient and developing decarbonisation strategies.
- From a technical perspective, they ensure the effective development of rate-matched CO_2 capture and injection.

Location and distance can be used to produce a rough overview of the geographic distribution of emission points and storage resources and hence to match one with the other. Such analysis can support the development of resource management strategies, but more refined analysis is likely required to develop concrete deployment strategies. Analysis can be refined by including estimated storage capacity, capture rates, injection rates, injection duration, transport pathways and project information (development timelines, lifetimes, operating projects, etc.). If the export or import of CO_2 is planned, these volumes and rates also should be accounted for.

CO_2 injection capacity ideally needs to increase faster than CO_2 capture capacity, or at a minimum at the same rate. Confidence in storage should drive capture deployment and can be increased by phasing the deployment of capture and storage. Phased deployment can increase confidence in a site's future performance by decreasing dynamic uncertainties. To promote the effective development and use of storage resources, sustainable injection rates and their duration should determine capture rates. Rate mismatch between capture and injection should be minimised. This is an important consideration for multi-source storage sites that are likely to receive CO_2 from sources with different capture rates.

Source-sink matching can also be used to develop rate-matched contingency plans to reduce the risk of unplanned emissions due to injection interruptions. In order for storage sites to be able to ensure that they can consistently inject captured CO_2, site operators should consider site-specific contingencies such as maintaining an injection rate margin. Regional co-operation agreements could also act as a contingency mechanism. Licence agreements and contracts need to outline how unplanned emissions are managed, but ultimately the aim is to reduce the risk of unplanned emissions as much as possible. Without adequate risk management, venting could be required. This would reduce the effectiveness of CO_2 management and present a risk to any capture facility operating in a jurisdiction with carbon penalties or caps.

Schematic of source-sink matching analysis



Notes: Line weights are used to represent different volumes of CO_2 from capture to storage.

CO_2 storage wells

Wells are designed to be fit for purpose for a specific activity. There are notable differences between CO_2 storage wells and other well types. CO_2 mixed with water is corrosive, so storage wells are sometimes constructed using corrosion-resistant materials, including special types of steel. Portland cement reacts chemically with CO_2, which can lead to dissolution; however, research shows that wells sealed with sufficient amounts of well-bonded cement can maintain their integrity when exposed to CO_2. Nevertheless, some projects choose to employ specialised cement. Special care should be taken during the well completion process – preparation of a well for activity – to ensure that neither reservoir nor well integrity are compromised. CO_2 storage relies on four main types of wells, each with its own purpose and design, size and cost considerations.

Exploration (and appraisal) wells are used to characterise storage resources, including their injectivity, containing features and performance. The orientation, design and depth of the exploration wells will determine whether they can be reused during site operations for another purpose. If they are to be reused, conversion usually occurs after site characterisation or site development. Data from both legacy (i.e. pre-existing) wells and the wells themselves may be used for exploration purposes, depending on well/data ownership, local regulation and design specifications.

Injection wells, often called injectors, are used to inject CO_2. Generally, injectors are purpose built or dual-purpose for exploration and injection. Legacy wells can be reused as injectors if they pass stringent requalification for the purpose of CO_2 storage.

Monitoring wells are outfitted with equipment to monitor the storage complex and CO_2 plume. Their depth and location, and the equipment they contain, will be dictated by their specific aim.

Brine extraction wells are used to extract reservoir fluids for pressure management. Not every site has this well type.

Info point: Well terminology

Some jurisdictions provide legal definitions for the terms: “legacy”, “orphan” and “abandon/abandonment”. This handbook uses the following definitions for these terms:

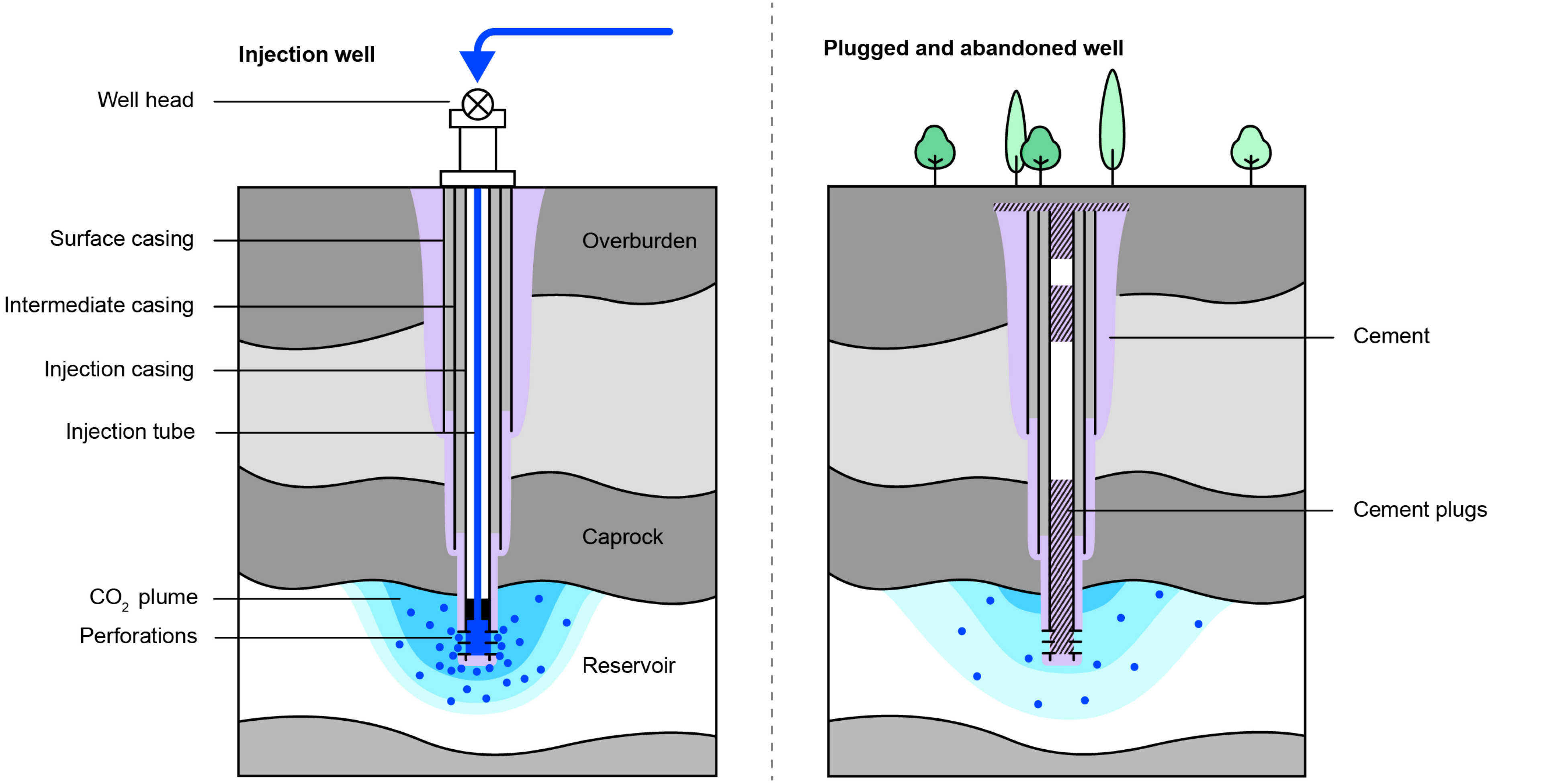
Abandoned wells are wells that are no longer in production and have been closed following plug and abandon procedures.

Legacy wells are previously drilled wells in a region or area. They can be actively producing, abandoned, suspended, orphaned or in an unknown state.

Orphaned wells are wells whose ownership cannot be determined. They may not be plugged or sealed properly.

Well abandonment, also known in some jurisdictions as decommissioning, is the process during which a well is cleaned and sealed, and its surface footprint removed.

Schematic of open and closed CO_2 storage wells



Notes: Figure not to scale. Casing requirements and cementing standards, along with decommissioning or plug and abandon standards, are jurisdictionally determined.

Measurement, monitoring and verification

Measurement, monitoring and verification (MMV) entails verifying the containment of injected CO_2, confirming the conformance of the site and increasing confidence in CO_2 storage operations. MMV programmes are a critical part of storage site operations. While they qualify and quantify the plume of CO_2, they do not detect every injected CO_2 molecule. Instead, overlapping and complementary techniques are used to observe site performance, detect early warning signs of CO_2 migration and verify that CO_2 is securely stored underground with minimal risk to human health or the environment. This provides confidence that injected CO_2 is located and behaving as expected. Verification of stored emissions is based on matched trends between measured and modelled behaviour. It is particularly important for sites that are affiliated to a carbon removal scheme or operating in a jurisdiction with emission reduction regulations. In the unlikely event of leakage, MMV results can be used to hold site owners accountable.

MMV activities include baseline measurements during site characterisation, followed by active monitoring during site operations, through to site closure. Post-closure monitoring aims to confirm effective site closure and complements the MMV activities that occur during operations. Typically, post-closure monitoring requirements are different from those during injection. MMV work plans should be site-specific and must meet or exceed regulatory requirements. To provide technical flexibility and to future-proof regulatory frameworks, policy makers should ensure that regulation addressing monitoring is technology neutral and risk-based. It should focus on the aims of monitoring rather than how to achieve those aims and should outline MMV reporting requirements. Each jurisdiction is likely to have slightly different MMV requirements.

Data collected by MMV programmes inform risk assessment, management and mitigation processes. These data are used to calibrate and validate predictive models and simulations. There is a feedback loop between MMV programmes and risk assessments. Since both need to be reviewed periodically, their review timelines should be synchronised. MMV programmes need to be flexible enough to allow for periodic updates, as new technologies are integrated to follow best practice and regulatory change and as the understanding of the storage site matures.

Over 50 different monitoring technologies are currently in use at CO_2 storage projects around the globe. No project will deploy every monitoring technique or technology. Risk-based MMV, such as that of the Quest project, provides safety assurances while promoting cost-effective deployment of monitoring technologies and optimised site operations. Equipment should be selected according to the MMV needs of a site, regulatory requirements, and cost. Lessons learned from ongoing or previous CO_2 storage activities suggest that monitoring pressure and temperature is a cost-effective way to reduce and manage multiple risk categories. Groundwater, surface and atmospheric monitoring can be valuable for risk reduction.

Components of an MMV programme

Elements of a measurement, monitoring, and verification programme

Reservoir properties	**Site location and land use**	**Monitoring phase**	**Monitoring aims**
Depth	Offshore	Pre-injection (Baseline)	Plume monitoring *Imaging and tracking the plume of injected CO_2 and the pressure plume*
Type	Onshore	Injection	Top seal integrity *Monitoring the integrity of the reservoir's top seal(s)*
Saline aquifer	Settled	Post-injection	Overburden monitoring *Monitoring for the presence of CO_2 above the storage reservoir*
Depleted oil or gas	Agricultural	Closure and Post-closure	Reservoir monitoring *Monitoring and quantification of subsurface processes in the storage complex*
Unconventional	Wooded		Seismicity *Monitoring aimed at detecting seismicity and earth movement*
	Arid		Wellbore monitoring *Monitoring the condition of wells and their components*
	Protected		Calibration measurements and monitoring *Measurements and monitoring used for model calibration*
			Near-surface CO_2 monitoring *Monitoring designed to detect CO_2 within 25 m of the surface*
			Surface emissions monitoring *Techniques used to detect and quantify any leakage that occurs at surface*
			Surface facilities monitoring *Techniques to monitor surface receiving and injection facilities*

Source: Adapted from the IEAGHG Monitoring Selection Tool.

Site closure and post-closure

The resource assessment process followed by MMV during operations is designed to demonstrate secure CO_2 storage. Post-closure monitoring demonstrates that closure of the site is effective. It also allows operators or owners of the site to confirm to stakeholders that there have been no emergent events, which can in turn increase confidence in storage.

A storage site can be closed after a period of post-injection monitoring. As part of site closure, any wells not needed for long-term monitoring should be plugged and abandoned in compliance with existing regulation and best practice. Given the limited number of closed CO_2 storage sites, it is expected that closure and post-closure best practices and regulatory requirements will continue to evolve. Legal and regulatory considerations are outlined further in the IEA CCUS Handbook on Legal and Regulatory Frameworks for CCUS.

Well abandonment will be governed by region- or country-specific regulation, but the fundamental principle is that functional barriers are in place to prevent CO_2 leakage or unintended migration. Cement is used at specific intervals – such as at the end of casings, in sealing units and at the surface – to isolate specific geological intervals and prevent fluid exchange. In some cases, the entire injection casing may need to be cemented to the surface. Well records, including their abandonment procedures, should be made accessible in a public database.

Once demonstrated that a CO_2 storage project is properly decommissioned and poses no unacceptable risk to health, safety or the environment, it can be certified as closed. Certification of site closure is usually a prerequisite for transferring liability. In most jurisdictions, monitoring will continue beyond closure.

Case study: Closure of the Ketzin pilot site

The Ketzin pilot site, Germany, was the first onshore CO_2 storage site to be operated and closed in Germany. The project had a two-stage abandonment procedure to confirm that closure techniques were suitable to trap the 67 kt of injected CO_2.

In 2013 the reservoir and caprock section of one well were plugged with specialised CO_2-resistant cement. Pressure and gas sensors remained in the cement plug for two years and detected no anomalies. In 2015 a core sample was taken from the cement plug to confirm that it had not lost its integrity due to interactions with stored CO_2. Site operators were able to prove that the cementing procedure was fit for purpose and the first well was then fully abandoned. This included removing any well casing above the cement plugs and backfilling the well with standard cement. The other three deep wells at the Ketzin site were abandoned using the same procedure in 2017. Liability was formally handed over to the competent authority in 2018.

Site transfer

After a site is certified as closed, the owner, operator or both typically remain legally responsible for stewardship and liability until such time that title may be transferred to another entity (typically the state). Stewardship responsibilities include site remediation, post-closure monitoring and associated activities such as routine maintenance on the MMV instruments. These responsibilities make up a small portion of CO_2 storage project costs. However, they represent continuing long-term liability that may be unacceptable to the private sector if it does not have a defined termination point.

The private sector may be more attracted to developing CO_2 storage sites if it is possible to transfer long-term liabilities and stewardship obligations to the state after site closure and a period of successful monitoring. Compared with sovereign states, CO_2 storage operators may have limited lifespans that prevent indefinite stewardship or financial assurance of liability. A regulated performance-based transfer process would provide storage operators and the state with a measure of confidence regarding the management of financial risks associated with decommissioned storage sites.

A competent authority could be one way for the public sector to manage long-term liability and stewardship. Such an authority could take over post-closure monitoring and certain liabilities associated with the site after title is transferred to it from the site owner. Conditions for transfer vary between jurisdictions with established mechanisms, but transfer is usually contingent on successful site closure and decommissioning. Both time-based and performance-based criteria can be considered when defining title transfer conditions. After the point of transfer to another entity, project operators are generally no longer responsible for the site or its liabilities. This may vary slightly between jurisdictions and is usually contingent on no malfeasance on the part of the operator.

Policy makers should ensure the following are included in a regulatory framework that allows for liability transfer:

- How, when and to whom title and liabilities can be transferred.
- Which liabilities are transferable and which, if any, must be borne by the operator post-transfer.
- The conditions to be fulfilled, or performance criteria to be met, in advance of transfer.
- How long post-closure monitoring is required.
- Funding mechanisms and financial requirements for post-transfer stewardship and post-transfer monitoring.

After site transfer, monitoring and stewardship needs may continue. These can be funded by insurance instruments, royalties or other schemes. In many jurisdictions, site operators or owners will be required to make financial provisions for post-closure stewardship responsibility and compensatory liabilities. Existing oil, gas and mining regulations could provide a model for how those provisions are structured in jurisdictions without existing regulation.

Assessment and development

Chapter summary

Storage resource assessment is often phased, allowing different actors to be involved at different points. A CO_2 storage resource atlas or database can provide a first assessment of resources and thereby supports the development of CO_2 storage. Atlases can often be compiled from existing data and geological maps. Both policy makers and project developers can use this kind of regional or national inventory of resources.

Similar to the use of geological surveys for other natural resource assessment, countries can conduct pre-commercial assessments to gain a better understanding of CO_2 storage resources. This is particularly effective at the regional level.

Each phase of the process is designed to build upon earlier work, but not every storage project will start assessment at the level of regional screening. Projects can build upon previously collected information or previous resource assessments. Some resources – such as those in depleted oil and gas fields – may already have been extensively studied. In such cases, drilling campaigns may not be necessary, though it will be necessary to reanalyse the data with CO_2 storage in mind.

Policy actions:

- Develop a national storage atlas or database using existing data.
- Develop and undertake regional and national data acquisition programmes.
- Provide financial and/or technical support to resource assessment.
- Ensure clear regulatory regimes exist for issuing exploration licences (or equivalent), permitting, environmental impact assessment, and monitoring and verification.
- Consider the value of digitisation of legacy data to support CO_2 storage resource assessment and development. Sources include: legacy well data (location, abandonment protocol, depth, etc.), geological maps, surveys, seismic data, and historical exploration permits and production licences for natural resources.
- Consider the value of having geological data publicly available and searchable in common data formats.

The assessment and development process is usually phased

The assessment and development process including data and modelling requirements

	Regional screening	Site screening	Site selection	Initial characterisation	Detailed characterisation	Design and development
SRMS category	Undiscovered to prospective resource	Play to lead	Lead to prospect	Prospect	Prospect to contingent	Contingent to capacity
CSLF capacity	Theoretical	Effective	Practical	Practical	Matched	Matched
Number of potential sites	Hundreds	30-50	~20	~5	3-5	1*
Description	Examination of storage resources on a regional (geologic basin) scale. Includes preliminary data gathering to identify promising regions.	Sub-regional analysis of resource potential based on existing data. Sub-regions should be evaluated using criteria defined during project framing.	Evaluation of selected sites based on predefined technical and non-technical requirements to produce preliminary development plans.	Site-specific assessment based on existing data leading to an up-to-date and costed site development plan for each viable site.	Site-specific assessment with technical studies to produce the data required to update reservoir modelling and for permitting.	Preparation of the site and site studies for permitting and FID.
Data requirements *Additive to earlier phases*	• Existing geological data to identify subsurface resources and their characteristics	• Geographic data • Social and demographic data	• Existing seismic data, well logs, stratigraphic records • Data purchases may be needed	• Existing geochemical and hydrogeological data	• New reservoir and well data required to characterise storage performance and containment	• Baseline monitoring data collection • Any additional data needed for permitting or FID
Modelling	Sedimentary basin atlas or CO_2 storage resource atlas	Screening assessment based on existing data	Simplified models using existing data	First-generation detailed models	Second-generation detailed models	Detailed models and development plans

* Multiple sites can be developed in parallel depending on the goals of a developer or project.

Notes: CSLF = Carbon Sequestration Leadership Forum; SRMS = Storage Resource Management System. Specific projects will start this process at different phases depending on the level of previous work in a country or region or on a specific storage resource. Investment needs are relative to overall cost of an individual project and may vary significantly according to the amount of data available.

Overview and project framing

Project development kicks off with project framing. This involves defining the boundaries of a project and the criteria that will be used for resource and site assessment. Following project framing, storage resources are assessed using technical and non-technical criteria. As a resource moves through the process, increasingly detailed development planning and engineering studies occur. Similar to oil, gas and mineral exploration, not all storage resources will be developable. This can be due to many factors, such as their location, the rate and duration of injection they can support or their development cost. For that reason, multiple sites should be assessed. At the end of each phase, sites which do not meet evaluation criteria are deselected, and only resources that fulfil the technical and non-technical criteria defined during project framing advance. This reduces exploration risk – the risk of sinking too much investment in an undevelopable resource – since technical studies become increasingly more detailed and costly as the process proceeds. It also enhances storage confidence.

Usually, regional screening, site screening, site selection and initial characterisation are considered precompetitive exploration, since these phases often do not require new data and may not require licences or permitting. The detailed characterisation step includes dedicated exploration and appraisal with the associated permitting or licensing requirements.

Developers certain of where they want to locate their project may be able to bypass certain phases of the assessment process. This can be the case for projects developed in conjunction with oil or gas activities, or for projects which benefit from previously conducted site screening or site selection.

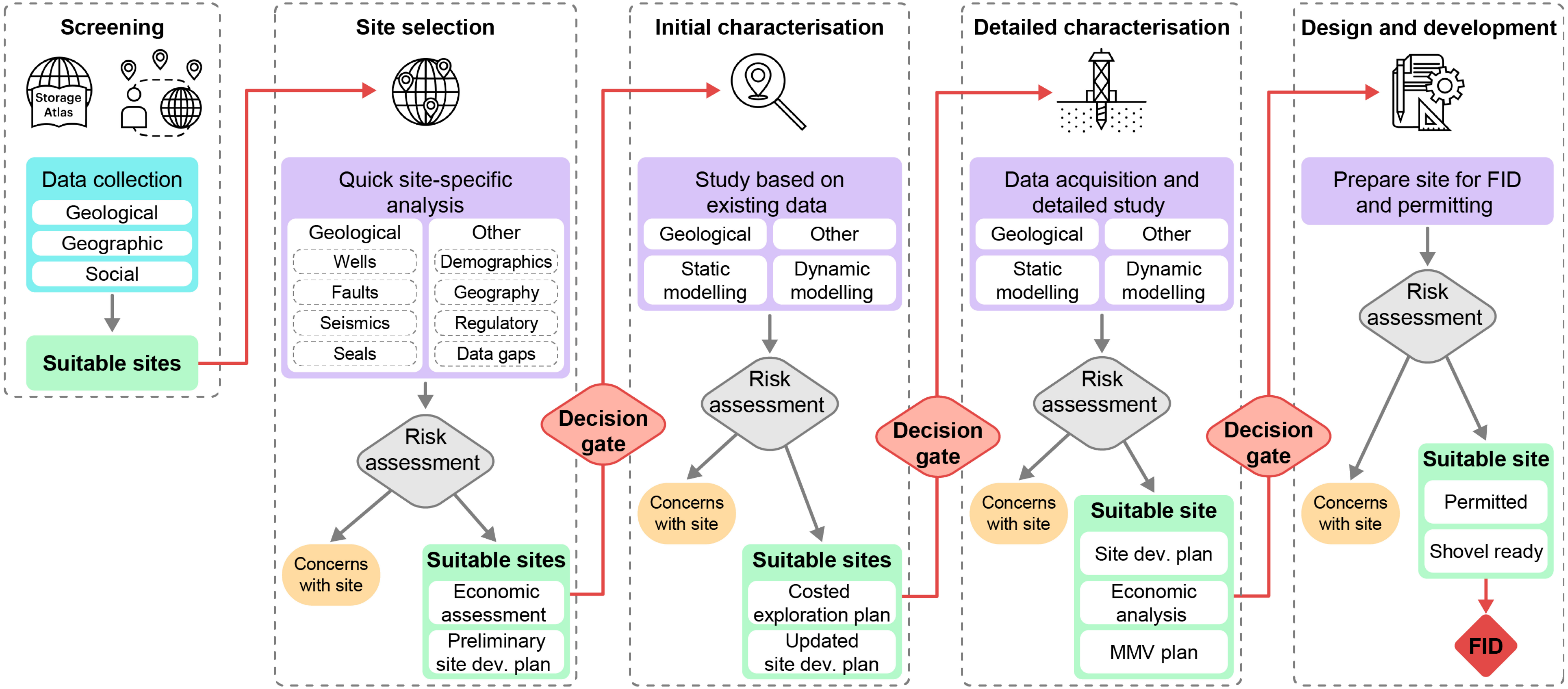
Categories to address during project framing

Category	Aspects to consider
Scope	• Define overall project including objectives and project evaluation criteria • Describe site screening, selection and characterisation processes
CO_2 strategy	• Develop a strategy for sourcing and injecting CO_2 • Outline implementation options along with risks and mitigation
Evaluation criteria	• Outline the technical, economic and social criteria that will be assessed during screening, selection and characterisation • Define how different criteria will be weighted when ranking sites • Define the storage confidence and injection rate needed to support resource development
Project resources	• Identify the expertise required during the site assessment process • Create a resource allocation plan that includes financial thresholds, contingencies and other resourcing risks
Schedule	• Create project schedule that includes milestones and contingency plans
Risk assessment	• Perform a project-specific risk assessment • Define a project implementation plan that includes decision gates at key stages

Source: Based on DOE/NETL-2017/1844.

Assessment and development workflow

Flowchart of the assessment and development process



Notes: Dev. = development

Regional and site screening

The screening phase of the assessment and development process is designed to identify CO_2 storage resources in a region (regional screening) and then eliminate sites, locations or resources that are unsuitable for further development (site screening) at that point in time. Resources are eliminated according to the criteria defined in the project management plan.

The expected outcome of screening is a portfolio of promising leads that can advance to the site selection phase.

Regional screening is performed over a large area, typically a geological basin. An area of interest is defined and then an inventory of the CO_2 storage resources present in that area is made using existing data and information. This phase of the assessment process is primarily focused on gathering existing data, which are then analysed during the next part of the screening process. Dynamic data are especially valuable since they inform injection rates and can be used to identify pressure constraints.

Site screening is used to identify sub-regions (leads) within a large area of interest that are potentially suitable for CO_2 storage. During this phase, promising sub-regions are identified and unsuitable sub-regions are eliminated based on the screening criteria defined during project framing. Technical criteria are assessed and understanding of storage resources is refined from the basin level to the sequence level using the data gathered during regional screening.

Considerations

In countries with national or regional CO_2 storage resource atlases or databases, regional screening or site screening may have already been performed. However, resource atlases and databases typically only include geological characteristics and may not include technical, socio-economic or regulatory considerations. As a result, more refined site screening may still be required.

Four main types of data should be collected and evaluated during screening:

- **Geological data** – Assessment of subsurface data focused on identifying the type of storage resource, along with its depth, seals and capacity.
- **Legacy well records** – Data relating to the status, location and technical properties (depth, orientation, etc.) of legacy wells can support rough assessments of seal integrity.
- **Regional geographic data** – Regional geographic data are important because they can determine site access. Protected and sensitive zones, urban centres, existing resource exploitation and existing pipelines can influence the suitability of a sub-region for storage development.
- **Social and demographic data** – Demographic trends and land use can influence the public perception of industrial activities and future CO_2 storage projects. These data should be assessed early since they will feed into project communication strategies.

Case study: Countrywide storage resource appraisal

The UK Storage Appraisal project was initiated in 2011 with USD 6.6 million (GBP 4 million) in funding from the Department of Energy and Climate Change. It was dedicated to assessing the United Kingdom's CO_2 storage resources. Its goal was to produce a resource assessment that was publicly available, robust and realistic. The results of the assessment are available in the CO_2 Stored database.

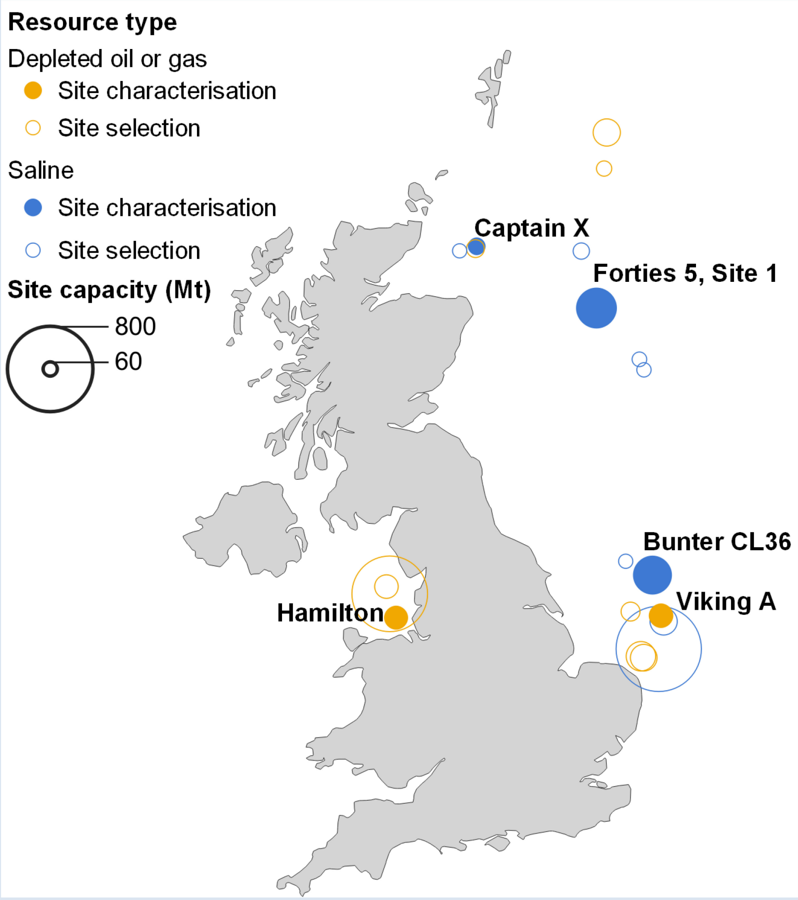
Regional screening: 579 storage resources were analysed.

Site screening: 37 sites qualified as "potentially strategic storage sites". Those sites were then ranked using six factors – capacity, injectivity, engineered containment risk, geological containment risk, development cost factor, and upside potential – to produce an inventory of 20 sites.

Site selection: Seismic data from the 20 selected sites were reviewed, and preliminary reservoir assessments were made using available well information. Sites were then reviewed and five were selected based on the goals of the assessment programme. The portfolio of five sites was then reviewed externally.

Site characterisation: The five selected sites proceeded to initial characterisation and are currently in various stages of characterisation and development. Each site was studied in detail during the Strategic UK CCS Storage Appraisal and it was determined that they have the ability to sustainably inject CO_2 at a commercial rate and for a commercial duration.

UK CO_2 Storage Appraisal programme portfolio of sites



Source: Cost data from Summary of results from the strategic UK CO_2 Storage Appraisal Project (2016).

Site selection

Site selection is a continuation of the screening process. During this phase, sub-regions, also known as leads, within the portfolio are evaluated using the predefined assessment criteria and those that are not suitable are eliminated. Data gathered during the screening phase are analysed more thoroughly. This phase can include the purchase of additional data if they are available.

The expected outcome of site selection is a portfolio of storage resources that can advance to site characterisation. To enhance storage confidence, each site should have a preliminary field development plan and initial economic analysis to document their suitability for characterisation. If the preliminary field development plan can demonstrate that it may be possible to develop the resource and achieve the desired injection rate, then it can support the development of CO_2 capture facilities and transport pathways. In the SRMS classification, the selected sites will be characterised as “prospects”, meaning that they represent a drilling target.

Considerations

Six technical and non-technical aspects should be evaluated during site selection.

- **Geological data** – Assessment of subsurface data, including seismic data, course stratigraphic and structure frameworks, core data and well records in order to identify storage reservoirs and injection zones. It uses existing data to characterise seals, trapping mechanisms, injectivity properties and resource capacity.
- **Legacy well records** – Assessment of legacy wells and the potential risks they pose using existing records. Well inventories should identify whether a legacy well is accessible or inaccessible.
- **Regulatory requirements** – Assessment of regulatory requirements for exploration, appraisal and site development. This can include mineral rights, pore space ownership, access conditions and operational requirements. Any regulation-dictated operational requirements such as maximum injection pressure, liability and containment should be integrated into the site selection criteria and the project management plan as required.
- **Models and modelling** – Modelling requirements and parameters should be identified. This should include boundary conditions and uncertainties. Developed models should incorporate existing seismic and geological data. Data gaps should be identified and a cost–benefit analysis should be made to determine the most cost-effective way to acquire new data that address data gaps.
- **Site suitability** – The geographic assessment made during screening should be refined during site selection and sites should be assessed to determine infrastructure requirements and monitoring needs. Additionally, the overall footprint (sometimes called area of review) for each site should be estimated using modelling results and any access constraints further investigated.
- **Social and demographic data** – Stakeholder outreach should begin with key stakeholders and communication strategies should be tested.

Initial and detailed site characterisation

Site characterisation is a continuous and interactive process during which one or more highly ranked potential sites are evaluated. It is divided into two parts, reflecting data acquisition requirements.

Initial site characterisation consists of an in-depth site-specific technical and non-technical assessment performed using existing data. If a site fulfils the assessment criteria, it can progress to detailed characterisation. Progression is usually contingent on a site having reservoir characteristics that support CO_2 storage, modelling that demonstrates a viable site, and up-to-date plans for public outreach, site development and site operations.

Detailed characterisation involves the acquisition of new, site-specific data and information through a dedicated exploration and appraisal programme. A detailed characterisation plan will be created for sites that advance into this phase to ensure that public outreach, data acquisition, reservoir modelling and site permitting are performed in a cost-effective and timely manner. Depending on the jurisdiction, certain exploration and appraisal activities may require a licence or permit, or equivalent.

Considerations for initial characterisation

Six main aspects of each potential site should be evaluated:

- **Public outreach** – A site-specific outreach strategy should be developed to ensure that targeted public engagement occurs as required. Since not all exploration will result in development, it is important to manage stakeholder expectations during the characterisation phase. If a viable outreach strategy or plan cannot be developed, then the site may not be viable.
- **Regulatory requirements** – This should build on the regulatory review completed during site selection. Dialogue with regulatory agencies to confirm the timelines and requirements for the permitting process should be entered into, and any project plans or definitions should be updated as required. Regulatory requirements relating to operations should be reassessed on a site-specific basis, with a focus on ensuring site viability and preparing for permitting.
- **Reservoir characteristics** – Building on the subsurface data assessments made in earlier phases, the geological, geochemical, geomechanical and hydrogeological characteristics of each targeted reservoir should be assessed using existing datasets. Developers may choose to purchase data sets to support assessment.
- **Legacy well assessment** – Building on the legacy well assessments in earlier phases, each legacy well should be individually assessed to determine the level of risk it may pose, whether it may require remediation, and if remediation is potentially feasible.
- **Modelling** – Reservoir characteristics will be integrated into models designed to characterise reservoir behaviour. Both static models and dynamic simulations will be used to design and optimise injection plans and to support risk analysis.

- **Site development** – The initial site development plan from site selection should be updated during evaluation of each aspect outlined here. If a potential site is found to be viable on the basis of public outreach, regulatory requirements, reservoir characteristics, modelling results and the up-to-date site development plan, then it may be recommended to advance to detailed characterisation.

Considerations for detailed characterisation

- **Outreach plan** – The public outreach plan or strategy developed during initial site characterisation should be assessed and modified to ensure that it accounts for any new activities that may occur during the detailed characterisation phase. Stakeholder dialogue and other outreach activities related to site design and development will also commence during this phase in preparation for environmental impact assessment and other requirements.
- **Data acquisition campaigns** – New geological, geophysical and geochemical data will be acquired and analysed. They can include 2D or 3D seismic surveys, the drilling of new wells, re-entry of legacy wells, and flow or injection tests. It should also include a detailed assessment of legacy wells. The purpose of data acquisition is to map and characterise the reservoir, its seals, and the geochemical, geomechanical and geophysical characteristics of the storage resource. This serves a dual purpose: to both determine site suitability and to establish pre-injection baselines.
- **Update models and simulations** – Geological models and reservoir simulations will be updated and refined using newly collected data.
- **Assemble necessary data for site development** – Assuming the site is found to be viable, it can move forward to permitting. All necessary documents, data and information should be gathered and prepared in line with jurisdictional requirements.

Case study: Simultaneous assessment of sites

The Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Initiative, funded by the US Department of Energy (DOE), provides substantial support to carbon storage projects. It focuses on sites that will be able to store 50 Mt of CO_2 or more over their lifetime and aims to develop storage projects that will support integrated deployment of CCUS between 2025 and 2030. It is divided into four phases:

- **Phase I** broadly aligns with site screening; 13 projects received a share of USD 15 million.
- **Phase II** aligns with site selection; USD 60 million worth of funding was divided among six projects.
- **Phase III** aligns with site characterisation and site design and development. Five projects have received funding under Phase III, and each is associated with a DOE-supported CO_2 capture project.
- **Phase IV** aligns with site design and development and construction.

In September 2022 the first call for proposals for **Phase IV** projects was released alongside an expansion of Phase III funding. Projects selected to receive Phase IV funding can receive up to 50% of total project costs. The CarbonSAFE programme effectively shares exploration risk between project developers and the government.

Site design and development

Site design and development is a natural continuation of site characterisation. It is when a developer finalises site planning and design in order to prepare for FID. By the end of site development, a storage site will be approximately shovel-ready, as long as it is not found undevelopable during the phase. In the SRMS, resources which advance to this phase are considered “contingent storage resources”.

The main outcome of successful site design and development would be a positive FID taken on the basis of the project’s FEED study, site development plans, business plan, up-to-date risk assessment and successful permitting. In the SRMS, a resource that has received a positive FID is considered “approved for development” and qualifies as “capacity”. Resources that are pre-FID but have all other necessary approvals are also considered “capacity”, but are only considered “justified for development”.

Project plans will need to account for the whole CCUS chain even if a project is storage-specific. Integrated full-chain projects should be aligned in their development timelines so that each part of the chain is commissioned at around the same time. Non-integrated projects will need, at a minimum, defined potential CO_2 sources and transport options. Given the early nature of the CO_2 management sector, it is possible that contractual relationships amounting to the whole annual injection capacity may not be confirmed in advance of FID. Developers can choose to incrementally scale up injection capacity. This can increase confidence in a resource while also reducing economic risk. Developers of sites with the aim of expanding injection capacity, or which only have a proportion of injection capacity locked in contracts before FID, should likely have some form of commitment (e.g. heads of terms or a memorandum of understanding) with emitters who are considering storing their CO_2 at the future site.

Considerations

Prior to FID being taken, storage developers will have completed the necessary development steps to ensure a fully informed FID process. Reaching FID is likely to be contingent on the site having:

- Completed engineering studies and project planning, including FEED, site development plan, business plan and an up-to-date risk assessment.
- Received the necessary environmental and development consents and permits from the appropriate regulators, including a storage licence or equivalent.
- Conducted an environmental impact assessment and received approval from the appropriate regulator.
- Secured approval from the appropriate regulator that the planned MMV programme meets or exceeds the regulatory requirements for monitoring until site closure.
- Firm CO_2 supply contracts for at least a proportion of annual injection capacity.

Case study: Permitting CO_2 storage in the United States

As with any infrastructure project, permitting CO_2 storage is complex, nevertheless, the process needs to be efficient and transparent. Ensuring that regulators have sufficient expertise and capacity is critical since this supports timely processing.

In the United States, injection of CO_2 is permitted under the Environmental Protection Agency's Underground Injection Control Well Class VI. Criteria for Class VI wells are stringent and very few Class VI permits have been issued. Only North Dakota and Wyoming have received Class VI well primacy, which grants state authorities the right to issue permits on their own. In all other states, Class VI permits are processed by the federal EPA.

Red Trail Energy was issued a Class VI permit in October 2021, seven months after it applied. The permit application included all necessary technical information describing the reservoir and injection operations. It also included plans for site closure, financial assurance, monitoring and emergency response. Since this permit was issued in the United States, where mineral rights are often controlled by the landowner, the permit application also included extensive documentation regarding pore space access. For United States-based projects, pore space access can significantly complicate project development.

This was the first Class VI permit that North Dakota issued and it was processed in an efficient manner. Its timely processing can support the further development of CO_2 storage in the state since permitting delays can substantially increase project costs.

Case study: Developing a depleted oil or gas field

As a rule, storage resources in depleted oil and gas fields will be better characterised than saline aquifers since these reservoirs will have been studied prior to and during hydrocarbon production.

The entity that manages oil and gas production at a specific reservoir or field will have reservoir-specific data and expertise. These can include knowing reservoir pressure (both current and initial), reservoir behaviour during production and reservoir geometry. The entity will also have an inventory of the wells in the area and will own site infrastructure. Therefore, owners of oil and gas assets that are nearing the end of their production lifetime should consider whether they could be converted to CO_2 storage sites.

The Ravenna CCS project in Italy is one example where this is occurring. Eni plans to develop a large CO_2 storage site in the Adriatic where it can convert depleted gas fields into CO_2 storage sites. Since the company has been producing gas in the region for many years, it has significant infrastructure both onshore and off that can be reused or repurposed for CO_2 storage. This can reduce the overall CAPEX of the storage project and accelerate project completion, and in general constitutes a more efficient use of existing resources.

Eni aims to demonstrate CO_2 storage at the Ravenna hub in 2023 and to commence with large-scale injection in 2027.

Technical assessment criteria

Chapter summary

Four technical criteria determine whether a CO_2 storage resource is suitable for development into a CO_2 storage site: CO_2 containment, monitorability, injectivity and capacity. As a resource proceeds through the assessment process, these four criteria are assessed in increasing detail to ensure that assessment is cost-effective and risks are minimised.

As with the assessment of hydrocarbon resources, confidence in a storage resource improves during the resource assessment process. As part of this, estimation of the injectable capacity of a resource is refined. The capacity of a storage resource decreases as assessment becomes more detailed. Initial capacity estimates are often based on corrected pore volume, a static measurement that can have little bearing on the injection rate that a resource can sustain and how long it can sustain CO_2 injection. As assessments are refined, they increasingly account for dynamic parameters such as injectivity and engineering design. This increasing confidence in a storage resource's capacity to hold CO_2 is reflected in a number of resource classification systems, including the SRMS. The resource capacity estimated during regional screening will usually be significantly higher than the matched – economic and risked – capacity of a resource that is being used as a storage site.

Policy actions:

- Consider if regulation is overly prescriptive in the timelines it defines for project development and early operations, or if it allows for reasonably flexible development timelines to account for potential project delays.
- Consider the value of digitising legacy data to support CO_2 storage resource assessment and development, including legacy well data (location, abandonment protocol, depth, etc.), geological maps, surveys, seismic data and historical exploration licences and permits and extraction history for subsurface natural resources.
- Support dynamic capacity assessments of CO_2 storage resources through research and development programmes, infrastructure programmes, and natural resource development activities.

Technical criteria determine storage site performance and security

Four interrelated criteria determine whether a CO_2 storage resource can be developed into a secure storage site with sufficient performance capabilities. Storage security is related to the **containment** of CO_2 and the **monitorability** of a site. Storage performance is tied to the **injectivity** and **capacity** of a storage resource. The resource assessment process is designed to study these criteria to determine how much CO_2 storage a resource can support.

Subsurface uncertainties relating to the geological properties of the storage resource are one of the largest sources of project uncertainty for a CO_2 storage project. Uncertainties can never be eliminated, but they can be reduced to an acceptable threshold using high-quality subsurface data, pre-injection monitoring and a robust MMV programme.

Technical studies become increasingly detailed as resources advance through the assessment and development process. The process is designed to optimise investment and minimise risk. As a result, containment, injectivity and capacity are assessed early, and reassessed often. The detailed characterisation phase of storage site assessment is the main phase when technical uncertainties can be reduced to a level acceptable to a project developer or regulator. It is also the most expensive phase of assessment due to the types of technical studies, such as well tests, that are required and therefore carries the most exploration risk.

Info point: Parallels in terminology between industries

Natural resources, such as minerals, oil and gas, are often discussed in terms of resources and reserves. Estimations of resources and reserves evolve with time on the basis of new discoveries, technologies and changing economic conditions.

Resources are estimated amounts of a geological commodity in a given geographic area. Resources can either be discovered (in place) when their location and characteristics are known, or they can be undiscovered (inferred) when they are thought to exist based on geological knowledge but are not confirmed. **Reserves** are known quantities of a commodity that are commercially recoverable. Similar to the term “recovery factor” used by the oil and gas industry, “storage efficiency” is used to describe the proportion of pore space within a targeted reservoir that can be filled with CO_2. Storage efficiencies vary between reservoirs according to their rock type, geometry and pressure.

These terms apply to CO_2 storage as well. While substantial CO_2 storage resources have been identified, only a limited volume of CO_2 storage reserves have been defined globally. Initial theoretical capacity estimations of storage resource capacity rarely account for dynamic considerations. Only a small fraction of this capacity will be usable to store CO_2. Substantial technical assessment of storage resources is required to define CO_2 storage reserves.

Timing of technical studies

Technical criteria and the assessment process

	Regional screening	Site screening	Site selection	Initial characterisation	Detailed characterisation	Development
Containment	• Confirmed on presence of regional seal or caprock	• Reservoir depth considered • Early screening of legacy wells	• Define containment models • Examine records for legacy wells and wellbore integrity	• Model reservoir pressure and containment based on existing data sets	• Update containment models based on newly acquired data • Assess legacy wells to confirm containment	• Confirm via well tests
Monitorability	Not assessed	Not necessarily assessed	• Initial assessment of monitoring needs and requirements	• Refine monitoring plan based on initial site development and operation plans	• Define monitoring plan	• Finalise monitoring plan and prepare for it to be submitted as part of site permitting • Commence with baseline monitoring if not already started
Injectivity	Not usually assessed	• Reservoir permeability and net thickness can be benchmarked against other storage projects as a proxy for injectivity	• Estimate injectivity based on any available extraction or injection history in the area, analysis of existing cores and/or hydrological tests	• Improve injectivity models and site development plans looking at numbers of wells required	• Perform injection tests as required • Project models and plans improved based on the results of technical studies	• Injectivity models and development plan improved based on the results of technical studies • Establish pre-injection baselines
Framework assignation	CSLF: Theoretical *SRMS: Prospective*	CSLF: Effective *SRMS: Play*	CSLF: Practical *SRMS: Lead*	CSLF: Practical *SRMS: Prospect*	CSLF: Matched *SRMS: Prospect*	CSLF: Matched *SRMS: Contingent*
Capacity estimation	Usually static	Usually static	Usually static and dynamic	Static and dynamic	Static and dynamic	Static and dynamic

Containment

Containment ensures that injected CO_2 will remain trapped within the boundaries of the storage reservoir and targeted zone. It is a function of reservoir geology, historical development and site operations. During development it is important to ensure the presence of containing features and during operation the continued security of the containment zone. CO_2 should not be able to migrate beyond the defined storage reservoir through either natural or engineered pathways (e.g. wells).

Containment relies on the integrity of natural geological features and the structural morphology of the reservoir. Reservoir studies should confirm the presence of geological features that can limit the lateral and vertical migration of CO_2 and effectively trap it in the intended storage zone. Such features can include sealed or closed faults, caprocks and certain types of fractures.

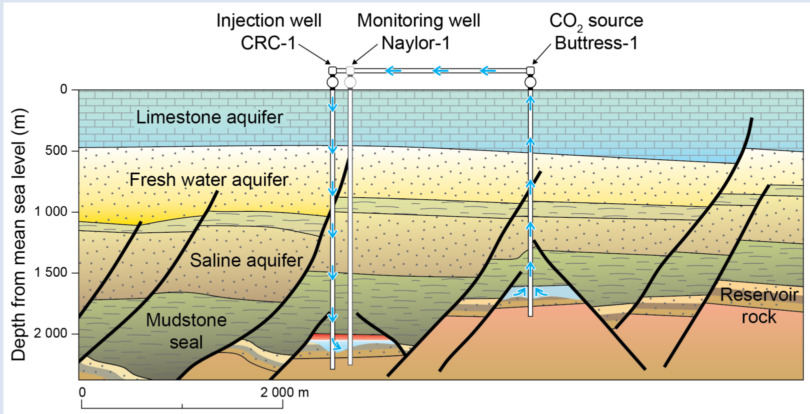
Containment also relies on the integrity of engineered structures, including new and legacy wells. Loss of containment can be caused by wet CO_2, overpressurisation due to injection and storage processes, or corrosion. Loss of well integrity is the main potential breach of engineering containment and can be minimised through proper engineering and site management.

The risks associated with containment are discussed further in Chapter 7.

Case study: Containment of CO_2 in a reservoir

The Otway Project in Australia was a pilot site for CO_2 storage in a depleted gas reservoir. During the project, natural CO_2 pumped from the Buttress gas field was injected into the Naylor gas field via the CRC-1 injection well. These gas reservoirs are less than 1 km apart, but they are isolated from one another by containing features. In the geological cross-section below, thick black lines are used to show the faults that laterally seal the two reservoirs. The reservoirs are sealed vertically by an impermeable mudstone caprock, shown in green.

Geological cross-section of the CO_2CRC Otway project



Source: Modified from J. Underschultz et al. (2011), CO_2 storage in a depleted gas field: An overview of the CO_2CRC Otway Project and initial results, *International Journal of Greenhouse Gas Control*, Vol. 5/4, pp. 922–932.

Monitorability

A storage site must be capable of being monitored. Site monitoring tracks conformance of the site (confirming the site is behaving in line with modelled behaviour), verifies containment of CO_2 and provides confidence that CO_2 injection and storage are not impacting humans or the environment in a negative manner. If CO_2 plume migration and pressure propagation cannot be adequately monitored, the suitability of the site should be reconsidered.

Monitorability of a site is influenced by a number of factors, including access, other activities in the area, and technical factors such as depth and resource type. For example, wind turbines (both on and offshore) can provide storage sites with a source of power and communications, and act as anchors for certain monitoring equipment. At the same time, they can also affect project seismic surveys and continuous seismic monitoring. Since CO_2 storage resources are immovable and may be a critical natural resource, it is important to consider how nearby activities or activities co-located with CO_2 storage sites may affect their monitorability.

Monitoring requirements should be assessed early in the development process so that a fit-for-purpose, site-specific MMV plan can be established. Some aspects of monitoring start either during detailed characterisation or site development and continue long beyond the end of CO_2 injection. Baseline monitoring is used to establish an estimate of initial site conditions, including partial and temporal variabilities that may be present. Monitoring during injection focuses on site integrity and changes in reservoir conditions, while post-injection and post-closure monitoring is designed to confirm the effective site closure. Site monitoring equipment should be repairable to allow for failure, and it should be updatable to allow for new monitoring equipment to be integrated. Further details on monitoring are found in Chapter 3.

Case study: Monitoring of injected CO_2

The Illinois Basin-Decatur Project in the United States injected nearly 1 Mt of CO_2 between November 2011 and November 2014. This project's comprehensive MMV programme demonstrates the array of techniques that can be used to monitor a CO_2 storage project. The MMV programme for this project deployed more than 20 monitoring techniques over an 11 year period. Monitoring commenced two years before injection to establish the baselines, and continued for three years during injection and for at least six years post-injection. The monitoring zone includes the near surface to deep subsurface and examines the atmosphere, soil, shallow ground water, above the reservoir and its seal, and the injection zone of the reservoir.

This project was the very first Class VI permitted well in the United States and was designed as a research project. Commercially operating sites, such as Quest in Canada, will have scaled-down risk-based monitoring programme.

Injectivity

Injectivity is the ability to inject captured CO_2 into a reservoir at the required rate over time. A sustainable injection rate is a key parameter for storage projects. The **initial injection rate** is dictated by reservoir permeability, thickness and pressure, along with site design. The injectivity of a reservoir will decline over time, referred to as the **injection decline rate**. This is a function of reservoir properties, including stratigraphy, structure, geological heterogeneity, connectivity, geochemistry and site operations including how much CO_2 has been injected.

In the subsurface, rocks and fluids are at elevated pressure. Subsurface engineering, fluid injection and fluid extraction can cause local pressure regimes to change. Generally, the injection of CO_2 leads to increased subsurface pressure. Elevated pressures in turn cause injectivity to decline. The geomechanical conditions of the storage formation need to be assessed to evaluate injectivity and the potential for injection rate decline.

By simulating the flow dynamics at near-well and far-field scales and pressure changes, it is possible to evaluate the potential for injection rate decline and determine the injectivity of a site. Reservoir models and simulations become increasingly detailed as assessment and development proceeds. Since well placement, maximum injection pressure and well design all influence injectivity, there is a feedback loop between site design and reservoir modelling. By the end of site development, an injection strategy and a pressure management strategy will be defined. More on pressure management can be found in Chapter 6.

Case studies: Injectivity challenges

Near-wellbore resistance to injection

Sand from the reservoir or debris from drilling can clog the injection zone or injection well of storage sites. At the start of the Sleipner CCS project in Norway, injectivity was about 10 times lower than predicted. A well workover was performed to integrate a sand screen that better distributed injected CO_2. After the workover, injectivity was even higher than expected at the start of the project. Sand clogging of a brine production well also occurred during the early stages of the Gorgon Project.

Chemical or salt clogging

Loss of injectivity can occur when salts precipitate in the pore space of a reservoir. To mitigate reduced injection rates due to salt formation, a chemical solution that mitigates salt precipitation can be injected. The Snøhvit project in Norway did this.

Far-field reservoir effects

The Snøhvit CCS project shifted its injection zone after reservoir pressure was unable to dissipate due to geological barriers some 3 km from the injection well. CO_2 is now injected in a shallower reservoir using a new injection well.

Capacity

Capacity refers to the volume of available pore space in a target area. Often there is confusion regarding what is meant by the term capacity because estimates are derived in different ways for different purposes. Depending on how capacity is estimated, it may not represent the actual usable capacity of a reservoir. In 2007 the Carbon Sequestration Leadership Forum provided definitions for different capacity estimates that are still in use today:

Theoretical capacity is a regional or national first approximation of capacity. It estimates the amount of pore space available for injected CO_2 to occupy; however, it does not account for the fact that injected CO_2 will only fill a fraction of available pore space.

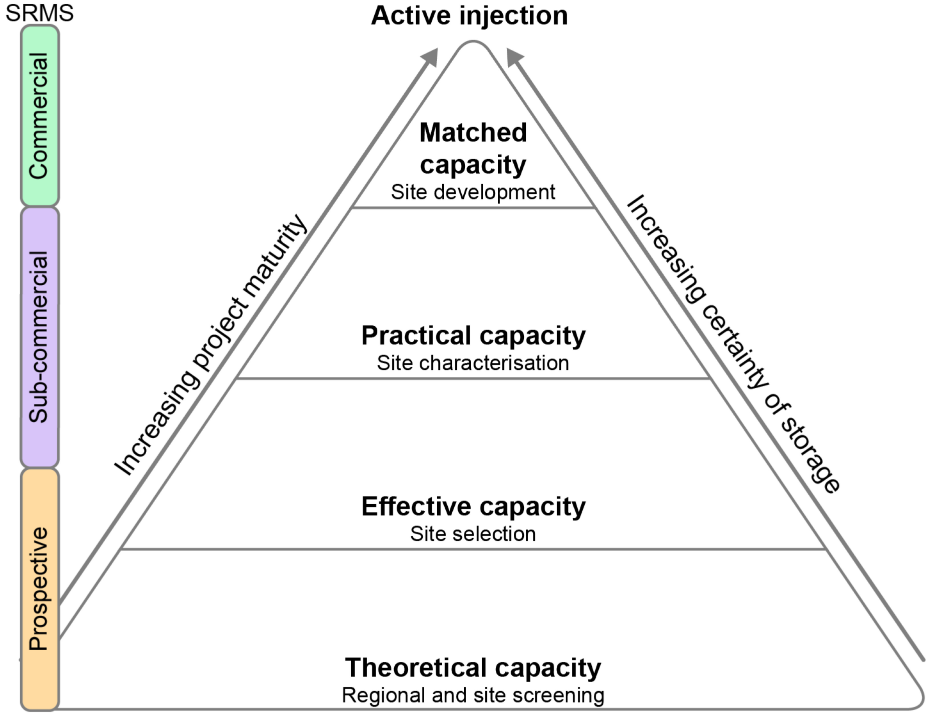
Effective capacity is an estimation of the theoretical amount of capacity that can be accessed and meets necessary geological and engineering criteria. It is often estimated using corrected pore volumes.

Practical capacity is a capacity estimation that accounts for technical, legal and regulatory, and infrastructure requirements and restrictions. Some economic criteria may be included.

Matched capacity is an economic risked practical capacity that is matched to emitting sources. Matched capacity estimations are constrained by the practical constraints outlined above along with additional economic and funding restrictions. Matched capacity is sometimes used interchangeably with bankable capacity.

A pyramid is often used to show how storage resources advance through assessment. While this visualisation suggests a scaled relationship between theoretical capacity and matched capacity, no such relationship exists.

The CO_2 storage pyramid



IEA. CC BY 4.0.

Source: Adapted from the CSLF Techno-economic resource pyramid (2005/2007).

Methods to estimate capacity

Capacity estimations can either be made using static methods or be derived from dynamic simulations. When capacity estimations are published, authors should note whether they were made using static or dynamic simulations. Uncertainty ranges (e.g. low, medium and high) should also be included.

Static capacity is a probabilistic estimation that accounts for uncertainties such as reservoir quality. Static capacity is provided as a function of corrected pore space and a storage efficiency factor. It does not consider physical constraints on pressure or rate. Static-based calculations have historically been used to estimate the capacity of a CO_2 storage resource. Many government-led initiatives estimate theoretical or effective capacity of CO_2 storage resources using static capacity calculations. This includes the atlases or databases of Australia, the European Union, Norway, the United Kingdom, the United States and others.

Static capacity estimations provide value in that they can establish the general location of storage resources and can often be made using existing data. However, they can be misleading because there is no strict relationship between static capacity and dynamic capacity. As a result, atlases and databases that assess theoretical capacity using static estimations may overestimate the usable capacity of storage resources.

Dynamic capacity is a deterministic estimation made from dynamic simulations. Simulations are used to assess the impact of specific parameters on the CO_2 plume and reservoir pressure over time. Dynamic models constrained with site-specific data are used to determine a safe and achievable injection rate and for how long injection can be sustained. This can, in turn, inform the design of capture facilities and support development of rate-matched capture and storage. However, dynamic modelling is more expensive and requires more data than static modelling, so it is often not used before the site selection or site characterisation phases.

Case study: Static versus dynamic capacity estimations

The EU GeoCapacity atlas uses static capacity and found the capacity of storage resources in the Paris region to range between 7.9 Gt and 27 Gt. In 2014 the region was reassessed using dynamic modelling to identify if any sites could provide a storage capacity of 200 Mt injected over 40 years. Based on available data, no site meeting that target capacity was found.

The dynamic assessment resulted in a regional capacity estimate of 180-270 Mt. That study found that the best resource in the region – Keuper Sud – has a storage capacity in the range of 54-140 Mt and 15 injection wells would be required to achieve that capacity. That work, along with other studies, demonstrates that practical capacity estimated using dynamic modelling is often significantly lower than theoretical capacity estimates derived using static estimation methods.

Constraints on matched capacity

Matched capacity is a function of geology and a site's engineering field development plan. It accounts for the geology of a storage resource, the characteristics of the developable area and regulatory limitations. A dynamic capacity assessment is needed to evaluate the economic viability of a storage site since it accounts for how injectivity declines with time.

Natural subsurface features, including faults and reservoir geometry, influence the matched capacity of storage resources. Engineered subsurface features, including legacy wells, can also restrict capacity by creating uncertainties. Subsurface features should be assessed early in the development of a site to ensure that the storage resource will perform suitably and safely.

Pressure and how it propagates outward from the injection zone influence both injectivity and capacity. The amount of pressure available for CO_2 injection is essentially the difference between the formation pressure (measured as bottom-hole pressure) and the fracture pressure of seals in a reservoir minus a safety margin. Some regulations define the maximum allowable pressure of a site as a function of a reservoir's fracture pressure.

Initial bottom-hole pressure depends on the pressure history of the area. In basins where there has been a long history of fluid extraction – groundwater extraction, petroleum production, etc. – the available injection pressure typically will be greater than that of a virgin basin that has not experienced any fluid extraction. Throughout the lifetime of a CO_2 storage project, the bottom-hole pressure will evolve according to subsurface activities in the same basin.

Regulatory regimes and permitting conditions can constrain capacity. Practical capacity and matched/bankable capacity estimations account for these constraints. Regulation will typically:

- Define the licensed area or lease of a CO_2 storage site. This includes where wells can be drilled along with the area in which the CO_2 plume must remain contained.
- Define the lease timeframe. Leases should be time limited and for other resources they typically endure around 25-30 years.
- Account for overlapping resource constraints, including any regulatory buffers between subsurface resources and CO_2 storage sites and jurisdictional boundaries.

Surface or near-surface restrictions can limit access to storage resources and constrain capacity. Such restrictions may relate to areas with critical infrastructure, such as roadways, pipelines, power lines, airports and urban exclusion zones; and environmentally sensitive areas, including national or regional parkland or marine parks, bodies of fresh water, wetlands and private property.

Risk management

Chapter summary

Risk management processes are a key part of CO_2 storage assessment, development and operations. Processes address socio-economic and technical risks.

Since risk exposure and impact vary throughout the lifetime of a CO_2 storage project, risk assessment and analysis are first performed during resource assessment. However, both continue throughout site operations and through to closure. Proper project management together with organisational competence act as a first line of defence against risk events, while regulation is the second.

Several techniques and strategies exist for the mitigation and remediation of technical risks, and pressure management is a key part of the planning and operations of any storage project.

Policy actions:

- Ensure that resources are assessed and operated in a safe and effective manner.
- Prioritise and co-ordinate resource development to mitigate resource interaction risks.
- Consider the role of independent evaluation of technical plans for due diligence.

Operator actions:

- Conduct detailed site assessments, optimise site design and manage pressure to mitigate performance risks.
- Ensure robust MMV programmes are in place to mitigate health, safety and environmental risks.
- Thoroughly assess legacy wells and natural seals, and ensure robust site management to mitigate containment failure risks.
- Ensure robust site characterisation and integrate monitoring to mitigate induced seismicity risks.

CO_2 storage projects have unique risks that need to be managed

The localised and project-specific risks posed by CO_2 storage must be balanced against the broad and far-reaching risks posed by climate change. As with any infrastructure project, risk management processes are integrated directly into CO_2 storage site development and operations. Risks can broadly be divided into two categories:

Socio-economic risks are risks that relate to social and economic factors. For CO_2 storage these risks mainly relate to public perception and market failure. Different stakeholders perceive the market risks associated with CO_2 storage projects differently:

- **Site developers or owners –** Market risks relate to sunk costs, uncertainties relating to resource development, and counterparty risk relating to CO_2 sources and potentially transport operators.
- **Regulators and policy makers –** Environmental, public safety and public perception-related risks are of a higher priority than pure market-related risks. They can include the risk of increased public scrutiny for CCUS projects that receive government funding.
- **Finance and insurance industries –** Risks relate to due diligence, and long-term liability that can affect investment and underwriting by increasing the market exposure of the insurer or investor.

Market risks and public perception are addressed in further detail in Chapter 8.

Technical risks are risks that relate directly to the CO_2, its injection, and storage operations. Technical risks can be grouped into five main categories. The probability and impact of technical risks will be site dependent, but in general both probability and impact are low to extremely low for properly developed and operated sites. Technical risks are addressed in more detail in Chapter 7.

Technical risk categories relating to CO_2 storage

Risk type	Description	Mitigation
Site performance	Risks primarily relating to injectivity and capacity that affect the performance of a site	• Detailed site assessment and optimised site design • Pressure management
Health, safety and environment (HSE)	Unsafe exposure to CO_2 as a result of CO_2 storage activities	• Appropriate site operations and management • MMV programmes to detect any leaks
Containment failure	Leakage of CO_2 or brine from the storage reservoir due to a failure of one or more containment features	• Thorough assessment of the natural seals in the selected reservoir • Robust site management • Thorough assessment of any legacy wells
Induced seismicity	Injected fluids can activate either known or unknown faults and cause seismic events	• Robust site characterisation • Integrated monitoring to detect subsurface and surface pressure changes
Resource interaction	CO_2 can interact with other subsurface resources; interactions can be positive, negative or neutral	• Regulation of the development as required • Prioritisation of natural resource development based on interaction risks and resource importance

Note: There is overlap between these risk categories.

Risk management in CO_2 storage

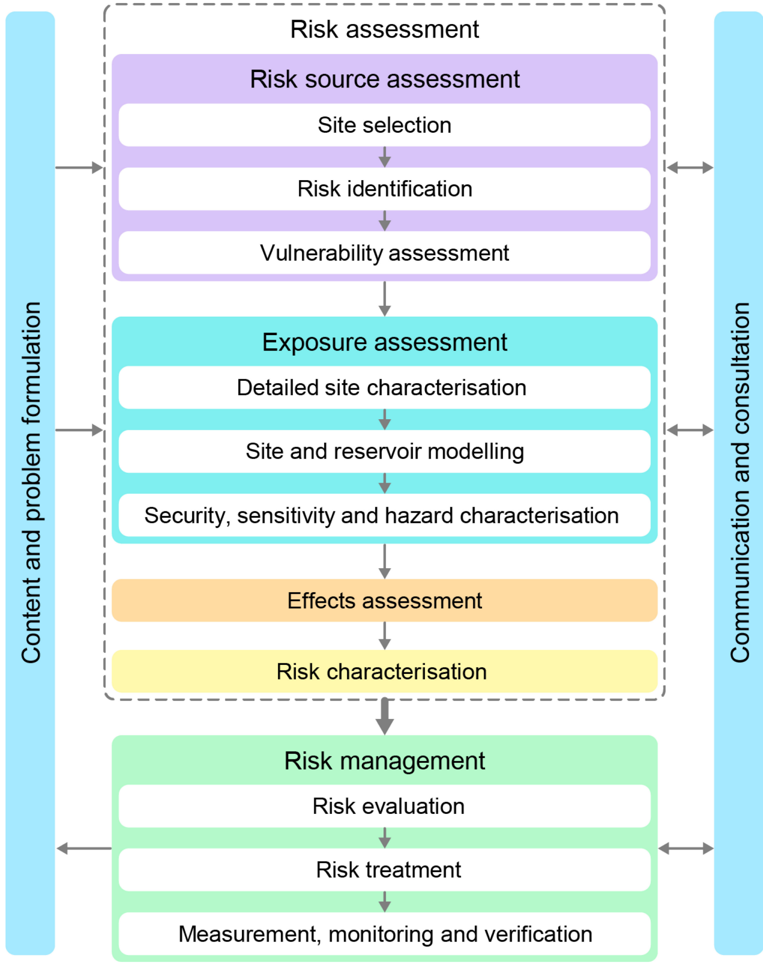
Risk management is a process whereby risks are identified, evaluated and prioritised; then risk monitoring and mitigation strategies are developed and implemented. CO_2 storage comes with its own specific set of risks, and existing standards and best practices can be adapted to support risk management processes in CO_2 storage. Storage resources should be developed only when technical risks are sufficiently low and can be mitigated. The progressive scale-up of sites can reduce subsurface uncertainties and in turn risk.

Specialised expertise and competencies underpin safe resource development and site operations (see Chapter 3). Competent site operations, robust site assessment and effective regulatory oversight underpin risk management and contribute to CO_2 storage security.

Risk exposure and impact vary throughout the lifetime of a project. Site-specific risk management programmes should account for this and be dynamic rather than static. They will need to evolve in response to advances in fundamental scientific understanding, changes in regulation, and in response to the results of MMV programmes.

MMV programmes should be assessed during permitting and then periodically reviewed. There should also be a defined procedure for reporting MMV results. Permits should only be issued to sites and projects where there is high confidence in the long-term security of injected CO_2.

Risk management framework for CO_2 storage



Source: Reproduced with modifications from IEAGHG (2009), Technical Study, Report Number: 2009-TR7.

Risk assessment and analysis

The assessment and analysis of risks, especially technical risks, form a key part of storage site development and operations. Risks are evaluated and assessed based on their probability (frequency of occurrence) and their magnitude (severity of their impacts). Often, risks will be scored according to their probability and severity – both mitigated and unmitigated – which allows them to be mapped onto a risk matrix. Risks that are highly probable or very severe, or both, will need to be evaluated in detail.

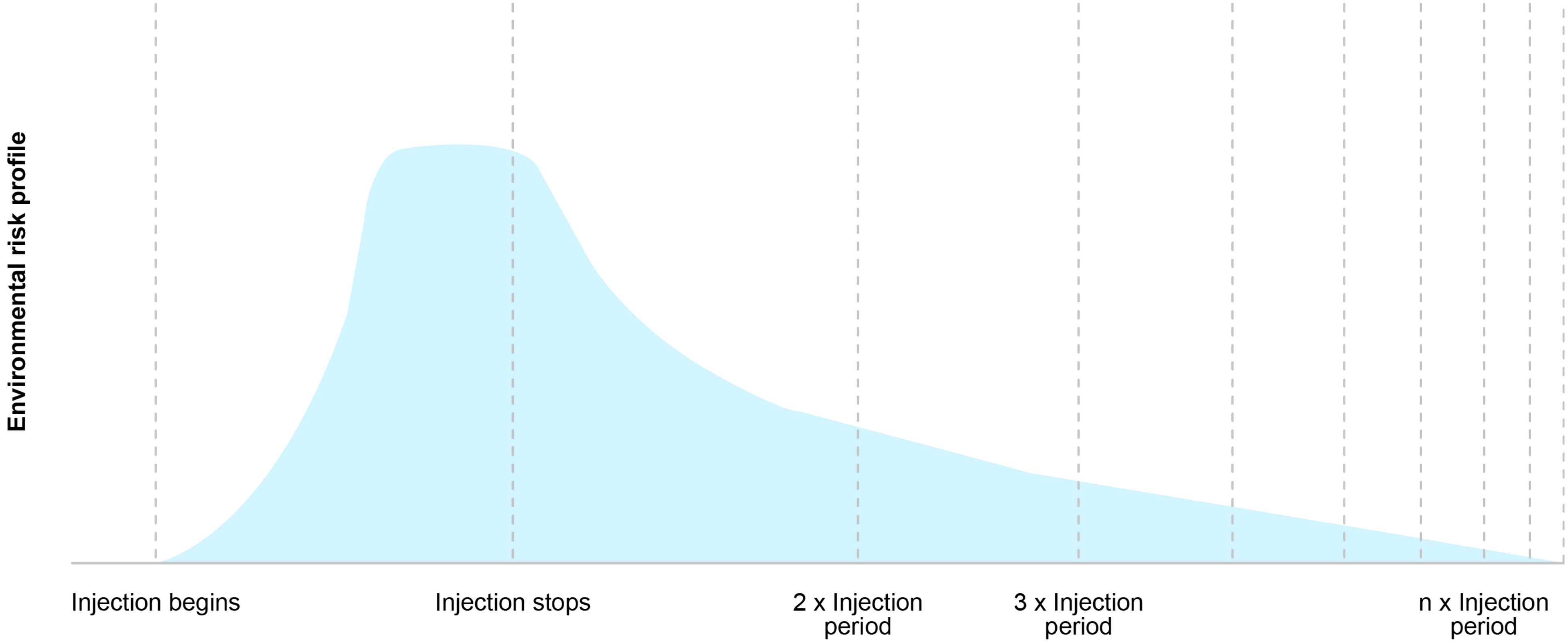
During project framing, the project manager should define priority risk concerns, acceptability thresholds and acceptability criteria. Acceptability thresholds will often be based on criteria such as impacts on health, safety and the environment, cost, reputation and project schedule, and technical considerations.

Technical risk assessments rely on data acquired during the resource assessment and development process and from MMV programmes. Storage complex and plume models are created from these data and they underpin the basis of many technical risk assessments. These assessments should be periodically re-evaluated. For operating CO_2 storage sites, risk assessments should be performed or updated on a yearly basis at a minimum. Annual project meetings can be used to update risk databases and discuss new or emerging risks. For resources under consideration for development, risk assessments should be performed at least once in every phase after initial regional and site screening.

The assessment and management of technical risks have advanced significantly in the last decade. A number of different risk assessment tools – including databases, performance assessment models, workflows and best practices – have been greatly refined or developed during this period. There is no current consensus regarding the time period used for risk assessment of a CO_2 storage site, although most projects use at least a 1 000+ year time horizon. Recently, there has been a move away from qualitative risk profiles towards a combination of qualitative profiles supported by quantitative indicators. Qualitative risk profiles remain an extremely valuable tool, especially for communicating environmental risks through time. Risk assessment practices will continue to improve as CO_2 storage is deployed more widely and more data can be used to validate system-level models.

Project developers and operators will have different risk thresholds according to their individual tolerance for risk, project plans, etc. Regulators will also need to decide on their priority risk concerns and ensure that they define thresholds for those risks. The resulting regulation should be neither too lax nor too stringent. Overly stringent regulation can place undue burdens on project developers and hamper storage development, while overly lax regulation could decrease public acceptance of storage and potentially allow for risky sites to be developed.

Qualitative environmental risk profile for a CO_2 storage project



Source: Reproduced from S.M. Benson (2007), Carbon dioxide capture and storage: research pathways, progress, and potential, presentation given at the Global Climate & Energy Project Annual Symposium, 1 October 2007.

Risk mitigation and remediation

Risk management includes preparedness in case of a risk event. While CO_2 storage sites are selected and monitored to reduce risk as much as possible, risk mitigation is a critical part of safe infrastructure development and operations. Risk mitigation and risk response strategies should be communicated to stakeholders in a transparent manner. This can enhance community trust and promote a positive public perception of CO_2 storage.

Regulation typically requires CO_2 storage operators to define their MMV programme, and their response and remediation plans and submit them for review. Suitable monitoring in conjunction with a swift response if abnormalities are observed are an effective way of mitigating risks that may threaten the integrity of a storage site, the CO_2 it holds, and public health or the environment. Japan CCS's rapid response to the naturally occurring Hokkaido Eastern Iburi earthquake is an example of this. The earthquake occurred at 3:07 a.m. By 8:00 a.m. Japan CCS was able to confirm that there were no abnormalities in the facilities. At 9:37 a.m. it publicly confirmed that there was no abnormality in either capture or injection facilities.

Should a risk event occur, a range of remediation measures can be deployed to control, manage and minimise the impact. Remediation options and strategies will depend on the type of incident and the magnitude of impact.

Remediation strategies

- Injection should cease in the event of a major leak or induced seismicity above a defined threshold. Injection may need to be stopped permanently.
- Pressure management strategies such as brine extraction can be used if overpressurisation is observed. Brine extraction can relieve pressure by removing fluids from the reservoir. It can also potentially be used to change or control the pathway of a CO_2 plume.
- Water injection into the CO_2 plume can dissolve gaseous CO_2, leading to increased residual and solubility trapping. This can improve storage security and change plume behaviour. However, it may come with significant costs or risk of emissions.
- Pump and treat methods can be used if brine or CO_2 contamination of groundwater occurs. This method uses purpose-drilled wells to remove CO_2- or brine-contaminated groundwater from an aquifer. The water is treated at surface and can either be discharged or reinjected into the aquifer.
- Well workovers can be used to repair minor well leaks. Wells can also be sealed to prevent further leakage.
- In the unlikely event of well blowout, relief wells can be drilled and heavy fluids can be pumped to prevent fluids from the reservoir from flowing up and limit the quantities of CO_2 released. This is conventionally known as well kill or killing a well.

Pressure management

Reservoir pressure – how it changes in response to injection, and how it propagates in the subsurface – contributes to site performance and CO_2 containment, and is a component of most technical risks. Therefore, pressure must be managed carefully throughout the entire lifetime of a CO_2 storage site. Different types of storage resources will have different pressure considerations and the geometry of the storage complex – the reservoir and its seals – will also influence pressure management.

Depleted oil and gas reservoirs are likely to have a lower risk of overpressurisation than saline aquifers since extraction activities can lower reservoir pressure. It is considered safe to gradually repressurise the field to its initial pre-extraction pressure so long as repressurisation will not cause well integrity issues or change the flow patterns of faults and seals in a deleterious manner. Saline aquifers have typically not been subject to previous extraction and therefore uncertainties around reservoir behaviour and its response to pressure changes may be higher. In both resource types, there is minimal risk provided pressure is continuously monitored and pressure management strategies are in place.

Overpressurisation can potentially cause the seal to fracture, reactivate existing faults and fractures, and cause induced seismicity. At any given time, the maximum pressure in the system will be at the injection point(s). To assess and manage pressure, initial bottom-hole pressure measurements are taken during site characterisation. Bottom-hole pressure is monitored, often continuously, as part of MMV programmes.

In order to avoid overpressurisation, geomechanical fracture pressure thresholds for the reservoir and seals should be defined. Usually the maximum bottom-hole injection pressure is restricted to a fraction of the estimated reservoir pressure, the seal fracturing pressure or the fault reactivation pressure, whichever is lowest. Some jurisdictions choose to regulate this. For example, in Alberta, Canada bottom-hole injection pressure is limited to 90% of the estimated rock fracturing pressure.

Pressure and pressure management strongly influence site design, especially regarding injection-related parameters such as placement of injection wells and injection rate. Pressure management is both a mitigation measure for technical risks and a remediation technique. Requirements are site-specific and dictate the properties of the storage resource, site design and site operations.

There are a number of pressure management techniques and sites are not limited to deploying one. Injection-related techniques include lowering injection pressure or reconfiguring injection patterns. Brine extraction – where brine is pumped out of the reservoir to make space for CO_2 – may be used to lower reservoir pressure and for plume control.

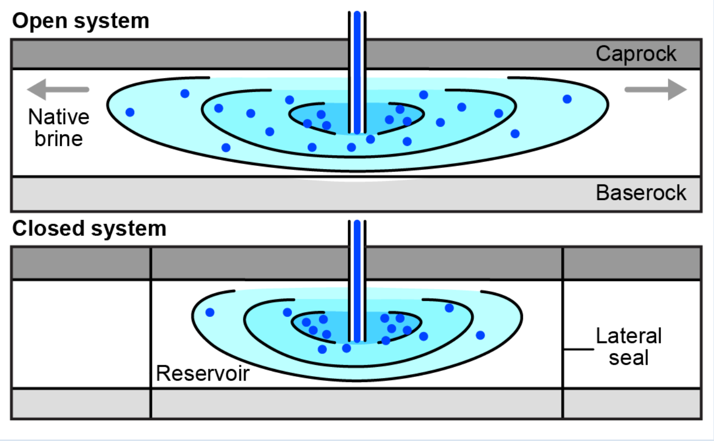
Info point: Open and closed storage systems

Open storage systems extend without lateral seals, allowing fluids to migrate laterally to make room for the CO_2 plume and allowing pressure to dissipate.

Closed storage systems are naturally sealed vertically and laterally by faults or other features. In closed systems, injection rates need to decrease with time to compensate for increasing reservoir pressure.

The idealised representations below demonstrate how reservoir geometry can affect fluid and CO_2 movement in a reservoir. In nature, most reservoirs will fall between these two systems.

Storage system geometry



Source: Modified from Q. Zhou et al. (2008), A method for quick assessment of CO_2 storage capacity in closed and semi-closed saline formations, International Journal of Greenhouse Gas Control.

Case study: Pressure management via brine extraction

Brine extraction – pre-injection, continuous or for remediation – can be a valuable pressure management technique allowing projects to maintain a stable injection rate. It comes with a suite of technical, financial and environmental considerations, including increased project costs and changing flow paths within the reservoir. Projects with brine extraction can consider a number of ways to manage the volumes of brine they produce. Brine can be reinjected into a different area of the reservoir or into another formation for disposal. Brine has a number of potential uses, for example it can be mined for valuable minerals, treated to produce fresh water or used by different sectors for various purposes; uses are site-specific and in some cases could offset extraction costs.

The Gorgon Project in Australia is the first dedicated storage project that includes water management (extraction) and water injection wells in its operational plan. The project extracts brackish water from the CO_2 storage reservoir to manage reservoir pressure. The extracted brackish water is reinjected into a different geological reservoir layer suitable for containment. This water management allows the operator to maintain injection of CO_2 at a consistent predictable pressure level.

Another major consideration is the solid material that may be co-produced during brine extraction. Material from the reservoir such as sand or carbonates can clog wells leading to lower extraction rates. Salt precipitation can also reduce extraction rates, but can be managed with standard industry techniques.

Technical risks

Chapter summary

It is important for CO_2 storage projects to have robust strategies in place to manage technical risks given the potential impact associated with a negative risk event. Technical risks of CO_2 storage can be broadly categorised into:

- site performance
- health, safety and environment
- containment
- induced seismicity
- resource interaction.

Generally these categories overlap and as a result risk management and mitigation strategies are often quite similar. In every case, detailed resource assessment, optimised site design and MMV programmes form the foundation for risk mitigation.

Policy actions:

- Determine acceptable risk thresholds and define strategies to manage risk events if they occur.
- Define a resource management strategy to ensure that resource contamination is minimised and that CO_2 storage can occur.
- Prioritise and co-ordinate resource development to mitigate resource interaction risks.
- Ensure that resources are assessed and operated in a safe and effective manner.

Operator actions:

- Conduct detailed site assessments, optimise site design and manage pressure to mitigate performance risks.
- Ensure robust MMV programmes to mitigate health, safety and environmental risks.
- Thoroughly assess legacy wells and natural seals, and ensure robust site management to mitigate containment failure risks.
- Ensure robust site characterisation and integrate monitoring to mitigate induced seismicity risks.

There are five main categories of technical risks

Technical risks relate directly to the CO_2, its injection and storage operations. During resource assessment and development, risks are identified using three main approaches:

- Screening criteria can be used to identify key risks.
- Historical operating data from similar geological settings can be used to identify technical risks.
- A more comprehensive approach uses scenarios developed from site- and project-specific features, events and processes (FEPs) to identify risks. FEP analysis is the most resource-intensive approach, but also the most common method to identify risks. It has been used by a number of CO_2 storage projects. The open-access Generic CO_2 Geological Storage FEP Database 2.0 developed by Quintessa provides a comprehensive starting point for FEP analysis.

The technical risks of CO_2 storage can be broadly categorised into risks relating to:

- site performance
- health, safety and environment (HSE)
- containment
- induced seismicity
- resource interaction.

These five categories overlap and risk management processes reflect that. The probability and impact of negative technical risk events should be low at CO_2 storage sites that have benefited from detailed resource assessment and are operated in line with industry good practice.

Site performance risks

Site performance risks are assessed during the assessment and development process to ensure that reservoir capacity and injectivity meet project needs. Storage resources will either be eliminated from further assessment or will advance to the next phase depending on how they align with predefined performance criteria. Reservoir modelling and site development plans will be regularly refined to ensure that site performance risks are low or can be mitigated.

Mitigation

Site performance risks can be mitigated through optimisation of site design, including pressure management. This will include an integrated analysis of well, near-well and reservoir conditions. Well development plans should be periodically reassessed during site development using the results of pumping tests, baseline measurements and modelling, reservoir modelling and formation pressure. Well completion methods should be decided on the basis of site-specific features and regulatory requirements. For example, sand and gravel packs in injection wells can be used to safeguard well integrity and injectivity, but may not be required at all sites.

Brine extraction may be included in development or operations plans to improve the sustainability of injection rates and relieve reservoir pressure. Multiple wells may be used to inject CO_2 with the goal of reducing injection pressure, increasing injection capacity or minimising near-well pressure build-up.

Case study: Pressure build-up affecting performance

As part of the Snøhvit LNG project in Norway, CO_2 is separated from natural gas and then injected into an offshore storage site. During project development, saline aquifers near the Snøhvit field were assessed for their storage potential.

In April 2008 the project started injecting CO_2. Within months, an increase in reservoir pressure was observed and pressure build-up became a concern. Despite changes to operations, pressure continued to rise. By late 2009 it appeared unlikely that the target formation would be able to support the rate and volume of CO_2 injection required by the Snøhvit project over its lifetime.

To address this, in April 2011 the project's injection well was worked over to allow injection into the water leg of the Stø Formation. Since a back-up had been defined during project development, the project was able switch injection zones and has been successfully injecting CO_2 ever since. In 2016 a second injection well was drilled into the Stø Formation in order to increase operational robustness and flexibility and reduce the risk for contamination of Snøhvit gas by injected CO_2; it has since been the main injector.

Health, safety and environmental risks

Elevated concentrations of CO_2 can lead to human health problems and environmental concerns. Provided sites are properly managed, the risk of toxic CO_2 exposure or of CO_2-related asphyxiation is extremely low. The highest risk for both is related to the sudden and unexpected release of CO_2 or the continuous release of large volumes of CO_2 in a relatively confined area. This could occur in the form of a well blowout, a large leak from the pipeline transporting CO_2 to the injection well, or from depressurisation of temporary tank-based storage on site.

In the unlikely event of a CO_2 leakage event, the impact on human health will depend on the nature, size and concentration of the leak. It will also depend on the proximity of humans to the leakage point, the length of exposure time and the topography of the area.

Ecosystem impacts caused by exposure to elevated concentrations of CO_2 depend on the severity and longevity of a leak. Catastrophic leakage events, while extremely unlikely, could significantly affect ecosystem dynamics and may lead to ecosystem instability. Plants and fungi tend to be more tolerant of elevated CO_2 than animals. Onshore, persistent CO_2 leakage could cause localised harm to plant life since CO_2 can suppress respiration and acidify soil if it accumulates. Offshore, persistence leakage could lead to localised seawater acidification that could affect some vulnerable organisms. However, marine ecosystems can tolerate a certain variation in CO_2 concentrations and acidity. Due to water movement and diffusion, an underwater leak of 1-10 tonnes per week would be likely to influence a few tens of metres.

Mitigation

HSE risks related to CO_2 exposure can be mitigated through site development and operations that follow best practice and regulation. MMV programmes should include monitoring of plume behaviour and implementation of active safeguards in order to reduce the risk of leakage that could lead to environmental damage.

Well operations should follow industry best practice and meet or exceed regulatory requirements. Given the corrosive nature of CO_2 when mixed with water, equipment should be regularly inspected and anti-corrosion measures implemented. Well workovers converting pre-existing non-CO_2 storage wells into injection wells should only be performed following rigorous well assessment. This type of well workover is relatively common in the CO_2-EOR industry. Depending on their specifications, it is also possible to convert CO_2 storage-specific exploration wells into injection wells. In such cases, the exploration well will be designed and completed to the specifications required for injection. The Northern Lights project plans to do this with its Eos well.

Info point: Demystifying well blowouts

Well blowouts occur when an operator loses control of well pressure causing fluid to migrate up and out of a well. Well blowouts can be caused by mechanical failure, flawed or damaged equipment, operational error or unpredictable circumstances (such as poorly sealed or unidentified legacy wells). Blowout rates in oil and gas activities have declined significantly in recent years due to improved technology, increased experience and changes in safety practices. These improvements are transferable to CO_2 storage.

In the context of CO_2 storage, well blowouts pose risks related to HSE, containment and public perception, and are a potential source of liability. While no well blowouts have been reported at dedicated storage sites, a number of well blowouts have occurred during CO_2-EOR operations in the United States. CO_2-EOR activities are different from dedicated CO_2 storage, but they provide the best analogue for understanding the types of blowouts that can occur. Four types of blowouts have occurred during CO_2-EOR activities. Blowouts during CO_2-EOR operations tend to be a consequence of operational problems tied to using CO_2 as an oil extraction medium. This suggests there is a lower risk of blowout with dedicated CO_2 storage than with CO_2-EOR. While blowouts can occur, the oil and gas industry has demonstrated that risks can be managed by successfully reducing the rate of blowouts. Additionally, the CO_2-EOR industry has demonstrated that it is possible to competently regain control of a CO_2 injection well.

Case study: General hazards of CO_2

While unlikely to occur if equipment is appropriately managed, both regulators and site operators need to be mindful of the risks posed by a sudden large-scale release of CO_2. No such releases have occurred during CO_2 storage activities, but examples can be found in other industries and from natural releases of CO_2. The risks posed by long-term low-level exposure should also be accounted for.

In the United Kingdom, CO_2 is classified as a "substance hazardous to health" and limits are placed to minimise workplace exposure. In 2011 the Health and Safety Executive published a report assessing the major hazard potential of CO_2.

The report found that CO_2 has an accident potential in line with other regulated hazardous substances. The range of impact of a CO_2 release varies depending on how the CO_2 is released (rate and volume) and in what form. The highest accident potential relates to a release of supercritical CO_2. Even though the report found that CO_2 has the potential to cause a "major hazard incident", it also found that the likelihood of such an incident is "very low" when risks are properly controlled.

The report highlights that knowledge and best practices relating risk management of supercritical or dense CO_2 are limited. Further research, codes of practice, standards and knowledge sharing on CO_2 handling will contribute to the safe operation of CO_2 storage sites and safe deployment of CCUS.

Containment risks

Containment failure is the most extensively researched risk category in CO_2 storage. Risks are site-specific, but their probability and impact are low to very low for a properly assessed, developed and operated site.

Containment failure can allow CO_2 or brine to escape the storage container via a number of pathways. This can have consequences for the environment – including underground resources, ocean, land and atmosphere – and for human health. Containment failure risks are pathway and time dependent. In a poorly assessed or operated reservoir, CO_2 could leak out quickly in large quantities or seep out slowly. Large leakages are very unlikely and should be prevented with effective site characterisation. They would most likely occur via engineered pathways, such as unidentified or improperly rehabilitated legacy wells, and should be quickly detected as they would produce abnormalities in monitoring data. CO_2 seepage can be more difficult to detect or monitor than larger leakages. Brine migration – which occurs as a result of CO_2 injection – can cause brine to be pushed out of the reservoir zone.

Injection typically causes reservoir pressure to increase. If adequate pressure management strategies are not employed, over-pressurisation can occur. This can potentially lead to containment failure. Post injection, reservoir pressure slowly declines and CO_2 becomes trapped by residual, solubility and mineral trapping. As a result, the risks relating to containment failure decline with time.

Mitigation

Major containment risks are mitigated during the assessment and development process. Storage resources should only be developed if uncertainties relating to containment are low and containment risks are within a tolerable threshold.

Containment assessments are used to identify leakage pathways and confirm the presence of containing features. They assess the top seal(s), faults, lateral structural features and engineered structures. Wells around a storage site are inventoried, their leakage pathways are identified and their baseline integrity is defined. Legacy wells are assessed using public records and privately held data. If necessary, they can also be re-entered for further assessment and re-abandoned. The construction and operations of purpose-built wells are also assessed. Wells can be scored individually on their likelihood of leaking and the potential size of a leak. As a rule, wells that meet CO_2 storage construction requirements will have lower containment risks than other wells.

MMV programmes, in conjunction with clear decision trees and measures that can be activated in the case of abnormalities, contribute to containment risk mitigation by tracking subsurface CO_2 migration and pressure propagation. Pressure management operations and altering injection rates and injection patterns can also contribute to containment risk mitigation.

Containment failure risks and their mitigation

Leakage pathway	Description	Mitigated probability	Severity	Mitigation
Lateral migration	The CO_2 plume or brine can migrate beyond the boundaries of the storage container or flow out of the container under spill points.	Very low	Low	• Robust characterisation of the storage container and its boundaries during detailed site characterisation and site development. • Integrating safeguards against lateral migration in site design when required.
Caprock failure or insufficiency	If the vertical seal fails, is incomplete or is damaged, CO_2 can migrate vertically into or beyond the caprock. Unintended damage to the seal can occur during poorly controlled drilling operations. The caprock can fail if pressures rise above its fracture pressure, but only if reservoir pressure is poorly managed.	Very low	Medium	• Assessment of the sealing capacity of the caprock. • Properly managed site operations. • Pressure management. • Monitoring of drilling conditions to reduce risk of damage.
Embrittlement of caprock due to cooling	Excessive cooling in the injection zone – caused by the rapid expansion of liquid CO_2 into a vapour – can lead to embrittlement of the caprock or reservoir and/or to caprock fracturing.	Low	Medium	• Managing the temperature and pressure of CO_2 injection. • Designing injection to manage caprock cooling.
Faults and fractures	CO_2 or brine can migrate along pathways created by faults, fault zones or fracture systems. Injection-related pressure changes can cause existing faults to reactivate and/or new fractures to form. Existing faults can also act as valves that release pressure and then close.	Very low to low	Low to medium	• Site-specific assessment of the risks posed by faults and fractures. • Maximising distance from the injection point to existing faults. • Pressure management.
Purpose-built CO_2 wells	CO_2 wells can provide a pathway for leakage if they are not properly constructed, operated and decommissioned.	Negligible	Low	• Regulation regarding well construction and operations. • Monitoring for well integrity throughout site lifetime. • Following up-to-date best practice guidelines and regulation for well construction, operations and abandonment. • Plugging and abandoning wells using dedicated cement plugs to seal in CO_2 and prevent leakage post injection.
Known legacy wells	Legacy oil and gas wells can provide a pathway for CO_2 leakage because construction and abandonment regulation and good practice were not designed with CO_2 storage in mind and may not be sufficient to ensure CO_2 containment. Depending on their construction and decommissioning, legacy wells could potentially allow CO_2 or brine to migrate from the reservoir into freshwater aquifers.	Low to medium	Site-specific	• Assessment and management of legacy wells, potentially including reopening and re-abandoning them in line with current regulatory requirements. • Avoiding storage resources with legacy wells; this could potentially severely limit access to storage resources. • Site-specific assessment of legacy wells and their leakage risk. • Maximising the distance between injection wells and legacy wells.

Leakage pathway	Description	Mitigated probability	Severity	Mitigation
Unknown legacy wells that pierce the seal or enter the storage reservoir	Old and abandoned wells have been identified as a critical potential leakage path. Such wells may not be properly documented or there may be low confidence in their construction and abandonment. Unknown wells could provide an unconstrained leakage pathway for CO_2.	Very low to medium depending on region	High	• In regions with historical subsurface activity (oil, gas, mining), extra care should be taken to search records for legacy wells. • Wells that enter the caprock or storage reservoir pose the most significant risk, so the depth of the storage formation should be compared to standard well depth in the region. • Reservoir and caprock studies and pumping tests can aid in the identification.

Notes: Probability and severity are site-specific and should be evaluated during risk assessment. The probability and severity estimations here are qualitative, not site-specific, and assume that sites have been assessed following best practice and risks are appropriately mitigated.

Case study: Injection rate affecting storage containment

The In Salah CCS project in Algeria operated between 2004 and 2011. It is considered an important case study for seismic monitoring, and microseismicity in CO_2 storage and risk management. Seismicity related to the project remained below a magnitude of 1 M_w (the moment magnitude scale). During the project, 3.8 Mt of CO_2 were injected into a geological storage site located near to the Krechba field in Algeria. The maximum permeability of the targeted zone was low, so three wells were used to inject CO_2.

In response to monitoring results and potential risk events, the project's risk register was modified on multiple occasions. The project identified that CO_2 was potentially injected at a rate that caused well pressure to exceed fracture pressure and initiated appropriate response measures including suspension in June 2011 after seven years of operations. To date, no leakage has been observed.

In 2008 data from InSAR (a type of radar-based remote sensing used to detect deformation land surfaces) and other monitoring techniques showed that there may be increased risk of CO_2 migrating northward and potentially outside the project's lease. In response, the project collected additional data, updated reservoir modelling, continued with monitoring and idled the northmost injection well.

In 2009 seismic monitoring showed that newly detected features could indicate fracturing. The project reduced CO_2 injection pressures and updated some of its monitoring techniques.

In 2010 CO_2 was detected in one of the project's wellheads, suggesting that well may have lost integrity. The project plugged and abandoned that specific well, increased the frequency of well inspections and placed additional focus on wellbore cement.

Info point: Well decommissioning, legacy wells and risk

Wells and boreholes of all kinds are decommissioned and abandoned after they have served their purpose. In most jurisdictions, the decommissioning of wells is regulated and determined by well type. Modern decommissioning and abandonment requirements usually include removal of internal equipment, sealing the well at one or more intervals with cement, and removing surface hazards. Most authorities also require the location and decommissioned status of the well to be reported.

Decommissioning procedures of CO_2 wells are designed to ensure containment of CO_2. Modern well decommissioning procedures for oil and gas wells, including plugging and abandonment, started around the 1950s. These procedures are designed to isolate the extraction zone and other geological formations with which the well intersects. However, they may not be sufficient to ensure CO_2 containment. For this reason, regulators should consider whether well decommissioning procedures should be updated in regions where there will be CO_2 storage. Requiring deep wells that pierce the caprock of storage resources to be decommissioned to CO_2 containment specifications could lower the cost of CO_2 storage development. Additionally, making well records publicly available can make it easier for storage developers to assess the site-specific risks posed by legacy wells.

In addition to the risks posed by known and properly decommissioned legacy wells, there are risks and uncertainties relating to undocumented, very old, orphaned or illegally drilled legacy wells. These wells are unlikely to have been closed in a manner that ensures CO_2 containment. For example, some onshore wells from historical oil and gas activity may have been plugged with tree trunks, gravel, lead, or not at all. Additionally, wells that have been deserted with surface equipment in place may have been illegally reopened, the mechanical seals of the equipment may have failed, or the surface equipment may have been tampered with. It may be extremely costly or even impossible to locate such wells and to assess their containment.

Offshore, developers and operators of gas fields may be best positioned to transition those fields towards CO_2 storage because they will be aware of the location, status and particularities of individual wells. Offshore decommissioning practices require the casing and wellhead to be cut off permanently plugged and abandoned wells. While the exact depth requirements vary, once subsea structures are removed it can be extremely difficult to relocate wells offshore.

Legacy oil and gas wells do not just pose leakage risks to CO_2 storage operations. Globally there are an estimated 29 million deserted oil and gas wells. These wells are a major source of methane emissions and can also lead to unexpected disasters, including explosions. Governments can contribute to methane reduction and to CO_2 storage readiness by enforcing existing well operation and closure requirements and by improving well decommissioning standards.

Induced seismicity risks

Seismic events occur when rocks fracture or when there is rock movement along a fault. Natural seismicity is a phenomenon caused by the Earth's movement, resulting in the natural failure of faults or the release of stress. Triggered seismicity occurs when human activity causes rock already under natural stress to fail or release stress. Induced seismicity occurs when human activity increase stress and strains in the subsurface and causes it to be released. Induced seismicity is typically low-energy microseismicity and can occur during activities related to oil and gas extraction, fluid extraction or injection, or mining, as well as being caused by artificial lakes and dams.

CO_2 storage is unlikely to trigger large earthquakes or reactivate faults through which CO_2 could leak. Generally, humans start feeling seismic activity between magnitudes 2.0 and 3.0 depending on depth, subsurface characteristics and distance. CO_2 injection may induce microseismicity, but the level of induced seismicity is expected to be very low and lower than the induced seismicity that has been observed during oil and gas operations, energy storage, wastewater injection and geothermal energy production. Induced microseismic activity with magnitudes below 2.0 has been detected at some CO_2 storage projects, including the Weyburn-Midale Project, the Illinois Basin-Decatur Project and the In Salah Project.

Felt microseismicity has been associated with CO_2 injection in one CO_2-EOR project,[5] but not with any dedicated CO_2 storage projects. No seismicity-related leakage has been attributed to any dedicated CO_2 storage project.

There are three main considerations regarding seismicity and risk with CO_2 storage:

- Seismic risk is project- and site-specific and should be evaluated on a per-project or per-site basis.
- Risk assessment tools such as probabilistic seismic hazard assessments can aid in determining the seismic risk level and whether risks can be safely managed.
- Public perception of seismic risks may have more impact on a site or project than the actual technical risk of seismicity.

Mitigation

Seismic risks can be mitigated to an acceptable level during site characterisation. Geomechanical assessments are used to identify, mitigate and manage the risk of induced seismicity and fault activation. They ensure that site operators have sufficient understanding of the geomechanical properties of the storage reservoir, its seals, the overburden (rock sitting above the reservoir)

[5] Multiple felt microseismic events occurred in Texas in 2011, it has been postulated that those events related to CO_2 injection, but investigation is ongoing into the cause of the microseismicity in that area.

and any features that occur in the area of review of a storage site. These assessments should place limits on the operating parameters – mainly injection pressure, rate and temperature – of a storage site, or storage sites within a single storage resource. These assessments will also inform the design of pressure management schemes and MMV programmes.

MMV programmes will monitor reservoir pressure before, during and after injection to ensure that the reservoir remains below the caprock fracture pressure. Integrated monitoring is deployed to detect surface deformation and microseismicity. This allows operators to monitor pressure changes, detect any escalation in the frequency and/or magnitude of microseismic events and respond if necessary. Response strategies can include changing the injection location or rate, both of which can have implications for pressure management strategies. In some cases, injection may need to cease.

Case study: CO_2 storage in an earthquake-prone region

The Tomakomai CCS Demonstration Project captured and stored 300 kt of CO_2 between April 2016 and November 2019. CO_2 was predominately injected into the Moebetsu Formation a few kilometres off the coast of Tomakomai, Japan.

On 6 September 2018 a natural earthquake with a magnitude of 6.6 M_w was recorded in Hokkaido, around 30 km away from the project at a depth of 37 km. Seismometers for the Tomakomai CCS project recorded a M_{JMA}[6] seismic intensity of around 5. Within one day, Japan CCS confirmed that there were no abnormalities at the facility and that they were verifying the status of injected CO_2. Pressure and temperature data from the project's monitoring array confirmed that there was no CO_2 leakage. In November 2018 Japan CCS published a research report on the impacts the earthquake had on the CO_2 storage reservoir. That report asserts that "it is inconceivable that there is any relationship between CO_2 injection and the Hokkaido Eastern Iburi Earthquake".

Following the earthquake, the project resumed CO_2 injection until November 2019 when the injection target of 300 kt was reached. The project is now in post-injection monitoring and the project's monitoring equipment has detected no microseismic events in the injection area since the start of injection.

[6] The Japan Meteorological Agency uses its own seismic intensity scale called the JMA. Rather than qualifying how much energy an earthquake releases, it qualifies how much ground-shaking occurs at distributed measurement sites.

Resource interaction risks

The risk of adverse resource interaction is low in properly developed and managed CO_2 storage sites. The likelihood of interaction between CO_2 storage activities and subsurface resources depends on the depth of injection, the type and depth of the resources, and site operations. Resource interaction needs to be assessed on a site-by-site basis. Regulatory mechanisms and contractual arrangements can manage potential interferences.

Storage activities can have positive, negative or neutral impacts on resources found within the injection zone, reservoir and surrounding rocks. Additionally, CO_2 storage development may be synergistic with the development of other subsurface resources. Due to their depth, shallower resources – including shallow groundwater, coal and most mineral deposits – are less likely to be exposed to injected CO_2. However, a leak of either brine or CO_2 from a poorly selected site could result in contamination of shallow resources. This is only a concern if containment fails. Deeper resources – including oil, gas, deep groundwater and geothermal resources – have a higher probability of interaction with CO_2 storage activities since they occur at similar depths.

Mitigation

Natural resources should be assessed on a basin-scale and their use planned out to ensure compatibility between various activities, including CO_2 storage. Resource co-ordination agreements and resource access prioritisation can support this. Resource development plans should be periodically reassessed to ensure they match current and future priorities. In some cases, storage resources may not be available until other activities within the same geological basin have ceased. Adverse resource interaction can be mitigated by ensuring containment of CO_2 and brine.

Resource interaction between CO_2 and subsurface resources

Subsurface resource	Positive impacts	Negative impacts
Groundwater	• Increased fluid pressure • Enhanced groundwater flow	• Changes in groundwater chemistry including pH • Potential mobilisation of metals • Displacement of brine into freshwater aquifer
Oil and gas	• Increased extraction of oil • Mitigating depressurisation caused by extraction • Reversal of subsistence	• CO_2 contamination • Disturbance of reservoir pressure
Coal and coal seam gas	• Potential displacement of methane	• Potential displacement of methane • CO_2 contamination of coalbed
Geothermal resources	• Exploration synergies between the two resources	• Cooling effects, which could reduce efficiency of geothermal fluids
Mineral resources	• Potential displacement of dissolved minerals leading to enhanced extraction	• CO_2 could react with dissolved minerals and plug pore space

Note: Methane can be a valuable potential by-product but is also a highly polluting GHG. Whether displacement is positive or negative will be project/site-specific.
Source: Adapted from IEAGHG (2013).

Commercialisation of CO_2 storage

Chapter summary

The CO_2 storage industry is being developed to support the decarbonisation required in energy transitions. Commercialisation of CO_2 storage will require collaboration and action by both the public and private sectors.

A number of existing business models can inform the development of CO_2 storage business models. It is likely that models will differ between geographic zones, accounting for resource availability, decarbonisation needs, and legal and regulatory frameworks.

CO_2 storage-specific business models will address storage-specific market risks and uncertainties, while accounting for the different types of CO_2 storage projects and project cost components. This will include defining how revenue can be generated and how projects can be financed.

Commercialisation will also hinge on public acceptance of CO_2 storage. Public awareness of CO_2 storage is generally low and dedicated storage is often conflated with CO_2-EOR. Increasing public awareness and improving public perception of the technology will support the development of a CO_2 storage industry.

Policy actions:

- Undertake precompetitive exploration, but recognise that not all exploration will result in developable resources.
- Assess whether an existing state-owned enterprise has the expertise and knowledge to assess or develop CO_2 storage resources.
- Collaborate with the private sector to define how CO_2 storage can generate revenue.
- Provide early movers with financing opportunities through grants, loans and other support mechanisms.
- Consider CO_2 storage-related liabilities and how they should be regulated.
- Determine how to implement risk sharing between the public and private sectors and how liabilities can be allocated.
- Align incentives to develop CO_2 capture and transport with confidence in storage.

CO_2 storage commercialisation requires business model development

Commercialisation of CO_2 storage will require concerted action by both the public and private sectors, including the development of CO_2 storage business models. While a limited number of dedicated CO_2 storage projects currently exist to inform regulatory regimes, insurance underwriters and project developers, decarbonisation efforts are driving the development of dedicated CO_2 storage and the business models to support it. Regionally informed, sector-specific business models are needed to support the upscaling and widespread deployment of storage; these can be informed by the models used in other sectors.

CO_2 storage-specific business models will need to address the financing of and revenue generation at CO_2 storage sites. Given the characteristics of CO_2 storage activities and the role they play in energy transitions, there is potential for CO_2 storage to be classified as an essential service and regulated as a utility. Policy makers should consider this since it could have a direct impact on business models.

Investment in CO_2 storage infrastructure is different from infrastructure investment in other sectors. The industry is still nascent and in many jurisdictions there is not a high level of confidence in policy support or in regulatory frameworks. Compared to other infrastructure types, CO_2 storage carries subsurface risk, has a long project duration and requires counterparty co-ordination with suppliers of CO_2. The design of CO_2 capture facilities and CO_2 transport infrastructure should be guided by the injection rate and duration of injection that individual storage resources can support. Confidence in CO_2 storage is needed to support the development of capture and transport, but contractual arrangements with CO_2 suppliers are also likely to be needed for storage sites to achieve FIDs. Within the CO_2 management value chain, CO_2 capture is overall more costly than CO_2 storage. However, CO_2 storage development is more capital intensive than capture in the stages before reaching the FID. These investments are at risk, and can generate no return if a resource is not suitable for development or if the FID is negative.

Since there is limited experience of operating CO_2 storage as a commercial industry, early movers will lead CO_2 storage market development. This should be a collaborative effort between regulators and project promoters to ensure that a robust business model develops and that storage resource acreage is appropriately managed. Risk-sharing arrangements should be considered because, compared to private-sector operators, governments may be better equipped to deal with some of the risks associated with CO_2 storage – such as long-term liability or pre-commercial exploration risk. Governments can thus act as a helpful risk-sharing partner to encourage the development of storage resources.

Elements to consider when defining a CO_2 storage business model

Elements of a CO_2 storage business model

Project type	Ownership	Financing	Revenue models	Financial risk management
Full-chain	Public	Funding sources	Contract for difference	Loan guarantees
Part-chain	Private	Emitters	PPP/PFI	Long-term contracts/policies
Storage hub	Public-private partnership	Fossil fuel suppliers	Cost-plus pricing	Revenue guarantees
Storage as a service		Energy consumers	Regulated asset base	Public underwriting
Expansion from full-chain		Public via taxation	Waste sector contracts	Insurance, self-insurance, private guarantees
		Consumers of low-carbon products		Price control (floors/caps)
		Capital		Fee regulation
		Public grants or loans		
		Equity		
		Debt		

Notes: PFI = private finance initiative; PPP = public–private partnership.

Project type

CO_2 storage activities can be developed within the framework of a full-chain CCUS project or as a part-chain project. Part-chain projects – storage-specific or with transport – may more effectively support the development of a CO_2 storage industry than full-chain projects. There are benefits and drawbacks to each approach.

Full-chain projects are integrated projects where capture, transport and storage are developed within a single project framework. Storage sites that are part of full-chain projects know where their CO_2 will be sourced from and what volumes will need to be injected. This contributes to lower uncertainty about CO_2 volume and counterparty risk. However, a full-chain approach can increase the probability and impact of cross-chain default.

Part-chain projects support the development of independent operators across the whole value chain. Breaking the value chain into its individual components allows specialised entities to develop, promoting innovation and competition. Existing entities with applicable expertise and competencies can also expand to offer CO_2-specific products or services. For example, a shipping company specialised in LNG could develop CO_2 shipping; a pipeline operator could develop CO_2 pipelines; and companies with subsurface expertise could develop and operate CO_2 storage sites.

Full-chain projects can morph into part-chain projects through incremental expansion in response to demand. Currently, two main models are emerging for part-chain project development:

- Large CO_2 (transport and) storage hubs developed to service industrial clusters that are simultaneously deploying CO_2 capture.
- Storage (and transport) infrastructure developed with a more speculative “if we build it, they will come” approach in order to offer access to CO_2 storage (and transport) as a commercial service. Projects that consider this approach are likely need some initial amount of assured CO_2 supply in order to justify investment.

Breaking the chain reduces the risk of cross-chain default but increases exposure to counterparty risk. Due to the lack of a concrete customer base, part-chain storage projects will have to manage risks and uncertainties regarding CO_2 supply. These can be reduced though source-sink matching on a regional basis, as can developing transport and storage hubs linked to large industrial clusters. To proceed with storage development and reduce market risks, some project developers are choosing phased site development. Phasing construction can reduce the risk of stranding oversized infrastructure, while still allowing capacity to increase in response to market demand. Policy makers can also reduce counterparty risk by introducing carbon prices and greenhouse gas regulations which serve as policy levers that can make emitting CO_2 more costly than capturing and storing. This can ensure a customer base. In all cases, measures should be taken to avoid the offshoring of emissions.

Case study: Storage as a service

"X" as a service, sometimes abbreviated as XaaS, is an increasingly common business model in the information technology sector. It recognises that specific companies may not be suited to managing in-house development and deployment of specific technology services. A classic example is data storage as a service, which turns data storage into an operational expenditure (OPEX). Customers pay a provider for access to data storage infrastructure, reducing their own need to make capital investments in infrastructure. This model supported the development of specialised data storage companies.

Both data and CO_2 storage require specialised skills and equipment to implement. Data storage is required by every enterprise and CO_2 storage may become increasingly required during energy transitions. As with data storage, a CO_2 storage service customer could treat storage of its captured CO_2 as OPEX (depending on the contract modality and accounting rules). This could reduce its exposure to storage-specific financial risks and allow it to focus on its core activities.

The Northern Lights project aims to deliver "carbon storage as a service". During development, only 0.8 Mt/year of CO_2 from two capture sites was assured. To reduce market risks, the project is being developed in phases. Phase 1, with a capacity of 1.5 Mt/year, should start operating in 2024. Thanks to significant interest in the project, development of Phase 2 (5 Mt/year capacity) started in 2022 with the drilling of a second well.

Case study: Development of CO_2 storage hubs

To stimulate the development of CO_2 storage hubs, the Canadian province of Alberta has implemented a competitive process to allocate subsurface CO_2 storage rights. In the first round, six proposals were selected to explore carbon storage hub development in Alberta's industrial heartland region:

- Meadowbrook Hub Project by Bison Low Carbon Ventures Inc.
- The Open Access Wabamun Carbon Hub by Enbridge Inc.
- The Origins Project by Enhance Energy Inc.
- Alberta Carbon Grid™ by Pembina Pipeline Corp. and TC Energy.
- Atlas Carbon Sequestration Hub by Shell Canada Limited, ATCO Energy Solutions Ltd and Suncor Energy Inc.
- Currently unnamed project by Wolf Midstream and partners.

The companies involved with each hub have been invited to further evaluate the suitability of each location for CO_2 storage. If demonstrated that the sites can provide safe and permanent storage, the companies can work with government on an agreement providing the right to inject CO_2 while enabling open access to emitters and affordable use of the hub. In March 2022 the Alberta government launched a second call for full project proposals for CO_2 storage hubs in the rest of Alberta. In October 2022 the government announced its selection of 19 further CO_2 storage hub projects spread across the rest of Alberta.

Project costs

Compared to CO_2 capture, fewer detailed cost studies are available on CO_2 storage. Since the number of operating projects is limited, very few cost studies are based on actual built costs. Similar to capacity, cost estimations that incorporate dynamic considerations – such as injection rate decline and pressure changes – tend to be more realistic. Project-specific cost studies that account for the technical, legal, regulatory and local market considerations are more accurate than large regional studies, which usually report costs as a range. Nevertheless, a few cost-related conclusions can be drawn from the limited number of studies and operating sites:

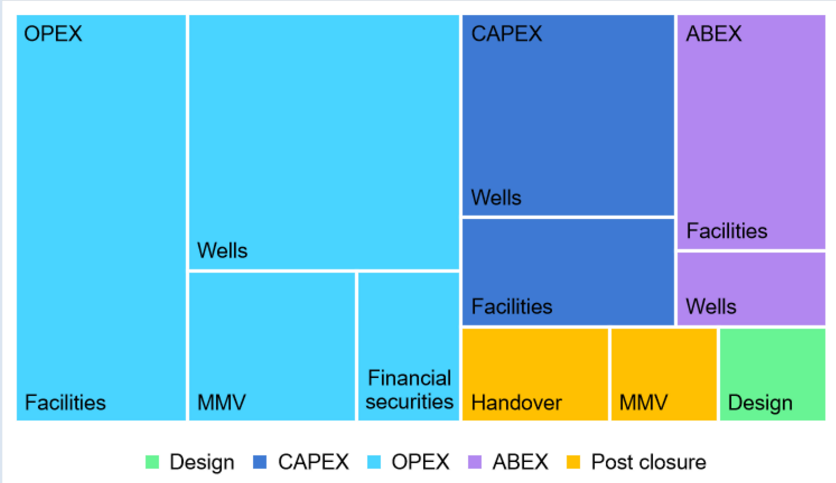
- Pre-FID costs are at risk and associated with resource assessment and site design.
- Onshore storage (assessment, development and operations) is typically cheaper than offshore storage.
- Storage resource capacity and injectivity strongly influence storage unit costs.
- Active pressure management can increase costs.
- Saline resources will usually require more extensive, and costly, data collection than resources in depleted oil and gas fields.

Costs vary significantly between storage projects and are regionally specific. They are usually expressed as a unit cost per tonne. This is a levelised cost, defined by the ratio of the total storage cost to the levelised volume of CO_2 stored. Total storage cost is calculated to be the real-term, pre-tax, breakeven price for a storage operator.

Case study: Cost distribution of offshore storage sites

The UK CCS Storage Appraisal project, funded by the Department of Energy & Climate Change, was a 12-month, USD 3 million (GBP 2.5 million) programme that assessed five storage sites from the UK's build-out portfolio. Each site was studied in detail, although remediation costs for legacy wells were not fully accounted for. Site-specific development plans for CO_2 transport and storage were developed, with each project designed to have a 40-year operational lifetime.

Relative weight of storage-related cost components



Notes: CAPEX = capital expenditure, OPEX = operational expenditure, ABEX = abandonment expenditure.
Source: Adapted from data deliverables 10-14 of the Strategic UK CCS Storage Appraisal project.

Cost components and comparative considerations

	Design and development expenditure	Capital expenditure (CAPEX)	Operational expenditure (OPEX)	Abandonment expenditure (ABEX)	Post closure (PC)
Description	Pre-FID costs including technical studies (including exploration-related drilling and well tests), due diligence, data purchasing, fees.	Site infrastructure including wells, well heads, surface facilities/platforms, injection systems, etc.	Costs relating to facility operations over the lifetime of the project.	CAPEX and OPEX specifically related to abandonment and closure.	Costs relating to post-closure MMV programme, including handover fees.
Share of total cost	Low–medium	High	Highest	Medium	Low–medium
Considerations: resource type	**Saline:** • Extensive data acquisition often needed • Project area may be larger **Depleted:** • Well characterised with abundant data • Accessibility depends on nearby oil and gas operations • May have existing transport connections	**Saline:** • Potentially lower available pressure margin • May require more wells to inject due to pressure* **Depleted:** • Possibility to reuse/repurpose existing infrastructure • May have numerous legacy wells that need to be re-abandoned*	**Saline:** • Potentially greater pressure management needs than in depleted oil and gas resources • Potentially more wells **Depleted:** • Potentially requires measures to prevent excessive wellbore cooling	**Saline:** • May have more wells that need to be closed, increasing cost **Depleted:** • Potentially higher decommissioning costs if infrastructure is reused	**Saline:** • Potentially requires a larger area of monitoring **Depleted:** • Potentially high remediation costs if remnant hydrocarbons leak
Considerations: resource location	**Onshore:** • More stakeholder engagement and involvement with landowners **Offshore:** • More expensive than onshore • Timing and availability of equipment	**Onshore:** • Larger risk of legacy wells that need to be re-abandoned* **Offshore:** • More expensive to drill and construct wells and re-abandon legacy wells* • Infrastructure is more expensive	**Onshore:** • May need more extensive MMV and stakeholder engagement **Offshore:** • Maintenance costs may be higher • Offshore labour costs typically higher than onshore	**Onshore:** • Abandonment procedures and closure requirements may be stricter **Offshore:** • Higher decommissioning costs due to offshore facilities and wells	**Onshore:** • Potentially higher remediation and/or rewilding costs • Potentially higher long-term liability burdens **Offshore:** • Potentially less long-term MMV required

* Depending on the project legacy well assessment, remediation and re-abandonment (as required) may be pre FID or post FID.

Notes: Pre-FID CAPEX costs such as exploration wells fall under “Design and development” and exploration wells may be converted into other well types depending on their design.

CO_2 storage cost evolution

Cost evolution is a major consideration for developing industries and sectors. Unlike the experience of many technologies, and despite an initial decrease due to learning and economies of scale, it is very possible that CO_2 storage costs could increase with time.

Store size and quality have the greatest influence on overall CO_2 storage costs. The most effective way to reduce CO_2 storage costs is to develop the right resource. Front loading data acquisition is a measure to reduce overall development costs by allowing the elimination of resources unsuitable for development early in the assessment process. Simultaneous assessment of a portfolio of resources means that data can be acquired on a regional basis, potentially reducing costs. Since not every resource will be suitable and uncertainties can affect operations in even the best characterised sites, contingency planning and back-up resources can be important. Assessing multiple sites in a region supports the development of build-out scenarios and contingency plans.

Economies of scale are linked to reservoir size and quality, and can strongly influence storage costs. Since wells are the costliest part of CO_2 storage, large resources with high injectivity will benefit most strongly from economies of scale. On a regional basis, smaller resources or those with lower injectivity should have a higher unit cost than larger resources with high injectivity.

Resource supply could contribute to increasing storage unit costs through time. Resources without specific access restrictions and with significant existing data are likely to be developed first. Following this, developers may target the highest quality, or largest resources. As a result, resource quality may fall and data acquisition requirements may increase. Since reservoir size and quality have the biggest influence on overall costs, a reduction in resource quality could result in increased costs during assessment, development and operations. If roll-out is not managed correctly, it could also lead to resource scarcity in some regions.

Learning-by-doing can contribute to optimisation in resource assessment and development as efforts become more refined. **Innovation** can lead to improvements in resource assessment, CO_2 injection and monitoring. For example, fibre-optic technology, artificial intelligence and machine learning approaches could reduce assessment and monitoring costs over time while improving the development process and increasing storage security. Injection well design optimisation can reduce well costs. Competency and technology **spillover** from other sectors could also reduce costs.

Storage-specific regulations and policies are key enablers of CO_2 storage and can put both upward and downward pressure on project costs through time. Overly prescriptive regulations, complicated permitting or regulatory changes and uncertainty can increase project costs due to project delays, increased compliance costs and less favourable project financing. Clear regulations and supportive policies can reduce or stabilise project costs.

Project ownership and the role of specialised CO_2 storage companies

Historically, governments have led the pre-competitive exploration and assessment of natural resources, usually via geological surveys. This can continue for CO_2 storage. Dynamic data collected by the oil and gas sector has substantial value to CO_2 storage assessments, but is often proprietary. Governments and data owners should consider how these data can be reused to support CO_2 storage development. In many cases, the private sector or public–private partnerships will lead on developing and operating storage sites because of the expertise required and precedents set by other types of infrastructure.

Entities specialised in CO_2 storage can support the growth of the CO_2 management sector, enabling economies of scale by developing and operating multiple CO_2 storage sites and by supporting a multiple source-to-sink business model. This can support efficient resource management and development. Dedicated entities can be special-purpose vehicles (SPVs), state-owned enterprises (SOEs), or companies specialised in CO_2 storage. Countries with a national oil company or other SOE that has subsurface expertise should consider if and how these corporate entities can support CO_2 storage site development and operations. Any entity dedicated to CO_2 storage will need to demonstrate the value proposition of CO_2 storage. This is especially true for early movers, who may face difficulties relating to public perception and may be moving forward without a clear CO_2 storage market.

Activities for an entity dedicated to CO_2 storage could include:

- Creating a portfolio of storage resources ranked by resource type, technical characteristics, access conditions and cost.
- Assessing storage resources and creating resource development plans. Resource development plans should include source-sink matching to identify the most suitable emission sources for each resource and define transport pathways.
- Managing CO_2 storage resource exploration and data collection.
- Developing CO_2 storage resources into operating storage sites.
- Ensuring safe site operations once commissioned.
- Complying with applicable regulation and contributing to the development of CO_2 storage best practices.
- Sharing data with researchers to support validation of CO_2 storage system models and the development of new or more optimised modelling approaches.
- Closing the storage site once it has reached end of life and continuing with long-term monitoring to ensure containment.

Much like the early days of the development of electricity and natural gas infrastructure, entry into the CO_2 storage industry has substantial start-up costs, requires specific competencies and has significant economies of scale. These characteristics often underpin natural monopolies. CO_2 storage needs to be safe, reliable and accessible to a wide range of emitters, so regulation will be needed to set the conditions for third-party access. This and market structure can prevent monopolistic behaviour even though using specialised entities can compound the risk of a monopoly.

Examples of entities involved in CO_2 storage resource assessment and development

Ownership	Entity type	Examples
Public	Government agencies including those whose mandate covers energy, petroleum, environment or geological surveys	• **Bureau de Recherches Géologique et Minières** (France) – France's geological survey, which has historically led the country's R&D work on CO_2 storage. Leads the PilotSTRATEGY Project aimed at developing CO_2 storage sites in Europe. • **Council for Geosciences** (South Africa) – Legal successor to South Africa's Geological Survey. Manages the country's CCUS activities, including the development of a pilot storage site. • **Department of Energy** (United States) – The agency tasked with managing US energy policy. Leads the CarbonSAFE initiative that funds studies on storage resources. Assembled the NATCARB CO_2 storage resource atlas. • **Norwegian Petroleum Directorate** (Norway) – The agency tasked with managing data from the Norwegian continental shelf and offshore oil and gas activities. This agency prepared the CO_2 Storage Atlas of the Norwegian North Sea.
Public	State-owned enterprises	• **Gassnova** (Norway) – Established in 2005 and tasked with the development of CCUS technologies and expertise and with advising the Norwegian government on CCUS. • **Gasunie** (Netherlands) – A natural gas infrastructure and transport company owned by the Dutch government. Promoter of the Porthos project in partnership with the Port of Rotterdam and EBN. • **Shenhua Group** (China) – Focused on activities in coal-based energy. Owners and former operators of the Shenhua CCS Demonstration Project, which injected ~300 kt of CO_2 into a saline aquifer between 2011 and 2015.
Mixed	Research organisations and/or consortia	• **CO_2CRC** (Australia) – A research centre dedicated to CCUS research. Owners and operators of the Otway International Test Centre, which is used to test different monitoring technologies and verification techniques. • **Petroleum Technology Research Centre** (Canada) – A not-for-profit that facilitates R&D and demonstration in CO_2 storage. Owners and operators of Aquistore, the CO_2 storage project associated with the Boundary Dam CCS project. • **SINTEF** (Norway) – A research organisation that is actively involved in the qualification and management of storage resources and storage sites. Leads the CO_2 Data Share Consortium, which hosts datasets from CO_2 storage projects.
Private	Interest groups	• **Oil and Gas Climate Initiative** (United Kingdom) – An industry-led initiative that has funded the Global CO_2 Storage Resource Catalogue. That catalogue takes existing CO_2 storage resource assessments and reanalyses them using the SRMS framework.
Private	Companies or corporate partnerships	• **Japan CCS Co., Ltd** (Japan) – An SPV founded in 2008 to develop CCS technologies in Japan. • **Northern Lights JV** (Norway) – A joint venture between Equinor, Shell and TotalEnergies. Developers of the Northern Lights Project. • **Storegga** (United Kingdom) – A company focused on the development of carbon reduction and removal technologies. Commercial lead of the Acorn Project and active worldwide in CCUS development.

Note: This table presents a cross section of organisations involved in storage resource assessment and development; it is by no means exhaustive.

Case study: An SPV dedicated to CCUS

Japan CCS Co., Ltd was established in 2008 by nine shareholders, which swiftly grew to 29. The company was specifically founded to develop an integrated CCUS project and CCUS-specific technologies. Currently, it has 34 shareholders whose expertise spans many CCUS-related sectors, including power, oil and gas and engineering.

Japan CCS works closely with Japan's Ministry of Economy, Trade and Industry (METI). Every year since 2008, METI has commissioned the company on projects relating to CCUS. This includes site surveys and site selection work between 2008 and 2011, along with the Tomokamoi CCS Demonstration Project from 2012. That project successfully injected around 300 kt of CO_2 into a saline reservoir between 2016 and 2019. It is no longer actively injecting CO_2, but is still actively monitoring the CO_2 plume. In addition to the above, Japan CCS has assessed potential CO_2 storage sites from 2014 through to today.

As a corporation dedicated to CCUS, Japan CCS has been able to build on the individual competencies of its shareholders and through that, it has successfully demonstrated CO_2 storage in Japan.

Case study: An SOE dedicated to CCUS

Established in 2005 by the Norwegian government, Gassnova has a mandate to support the development of CCUS technologies and knowledge through the CLIMIT programme. The company also advises the government on matters relating to CCUS.

Gassnova shares administrative responsibility for the CLIMIT programme with the Research Council of Norway. CLIMIT is a national programme for the research, development and demonstration of CCS technologies. Additionally, Gassnova operates the carbon capture test platform called Technology Centre Mongstad on behalf of the government and other shareholders.

As an SOE dedicated to CCUS, Gassnova supports CO_2 storage development in Norway by channelling state aid to the Longship CCS project. As co-ordinator of the overall project schedule for the Longship CCS project (which includes the Northern Lights Project), Gassnova is deeply involved with managing the cross-chain and counterparty risks in the project. Due to Gassnova's role as project integrator, the Norwegian state was able to accept the cost and risks associated with breaking apart the CCUS value chain and developing two capture projects separately from the transport and storage project.

Project financing

Investment in capital projects like CO_2 storage sites can accelerate growth within a region by supporting further economic development. Capital investment in CO_2 storage can come from public, private or mixed sources in the form of grants or loans, equity or debt financing, existing cash reserves and operational budgets. Specific project funding and capital investment are needed to advance the deployment of CO_2 storage. While it should complement investment in other parts of the CO_2 management value chain, access to CO_2 storage is paramount, so investment in storage should be a top priority. Due to exploration risk, assessment is usually funded by equity, while resource development usually has access to other financing propositions. One source of project funding can come from the tax system, either through incentives – such as in the United States under the 45Q tax credit – or via specific taxes levied on products or activities that have not been decarbonised.

Project funding can also come from emitters or fossil fuel suppliers following a "polluter pays" principle, whereby CO_2 storage development is financed through obligations or taxes on emitters. In the case of fossil fuels suppliers, researchers have recently suggested that imposing a "carbon takeback obligation" on the fossil fuel industry could reduce that industry's emissions and provide a low-risk and affordable pathway towards net zero emissions. Takeback obligations – requiring fossil fuel producers and importers to store a percentage of the CO_2 generated by the fossil fuels they sell – would increase progressively with time. In order to be effective, the takeback obligation would need to apply to the point of origin of fossil carbon and be linked to CCUS commitments or a country's nationally determined contribution. Such an obligation could accelerate storage development while capitalising on the oil and gas sector's existing subsurface competencies. Various mechanisms, including tradeable carbon credits, CO_2 removal certificates and premiums on low-carbon products, can also support capital investment in CO_2 storage.

Case study: Public grants to support a private project

The Quest CCS project, funded by Shell and the governments of Canada and Alberta, has captured and stored over 6 Mt of CO_2 ahead of its original schedule. The project also cost about 10% less than the original estimate. This project is paving the way for future projects that will no longer require government support.

Commissioned in 2015, Quest is a full-chain project that captures and stores emissions associated with oil sands processing. Project CAPEX amounted to USD 618 million (CAD 790 million) and the project received some USD 448 million (CAD 573 million) in support for activities prior to operations. The government of Alberta also contributes funding during operations based on the annual volume of CO_2 stored. The storage-related FEED amounted to USD 49 million (CAD 63 million) and storage-related CAPEX – excluding labour – to USD 31 million (CAD 40 million).

Revenue models

A successful CO_2 storage sector will need to generate revenue. Existing revenue models could be adapted for the sector.

A **contract for difference** is a contract between a buyer and seller that sets a guaranteed price for a product. One contracting party pays the other party the difference between the set price and the market price, the direction of payment depending on whether the market price is higher or lower than the set price. They are likely to have limited relevance for part-chain CO_2 storage projects beyond providing emitters with a premium that could offset a fee for CO_2 storage.

The public–private partnership (PPP) and private finance initiative (PFI) approaches are well-known revenue models that allow for flexible funding arrangements and support both construction and operational phases. The Quest CCS project was financed using this model.

Cost-plus pricing is when a fixed percentage is added to a unit cost to produce a defined return on investment. In the case of CO_2 storage, emitters would be charged a set fee based on the site's unit cost and the defined markup. This revenue model is most often used for government contracts and is sometimes criticised for not providing incentives to reduce costs. It may be unsuitable for private-sector customers. While cost-plus pricing may be a valid structure for early-moving CO_2 storage sites, it is unlikely to be a long-term revenue model for the industry.

The **regulated asset base** model is often used by public utilities. In this model, a regulator controls investment levels and rate of return. Since the model is well understood, it may be adaptable to the CO_2 storage sector. However, it may not provide the private sector with sufficient incentive to take on CO_2 storage-related risks and liabilities, especially those related to pre-FID resource assets and post-closure stewardship. Additional mechanisms to support CO_2 storage development and to reduce market risks may be required.

Waste sector contracts would see a fee being charged per tonne of CO_2 stored. This model is well understood and parallels can be drawn between waste management and CO_2 storage. However, the model often suffers from financing difficulties due to its reliance on short-term contracts and often insufficient cost recovery. Since CO_2 storage contracts are expected to be longer, the model may be unsuitable for CO_2 storage.

The main drawback of the above revenue models is that they do not include a mechanism for funding pre-FID activities. It is likely that a hybrid CO_2 storage revenue model will evolve over time and incorporate different aspects of other known revenue models. Evolving regulation, including tax credits and carbon taxes, can support or accelerate development of a revenue model for CO_2 storage. CO_2 removal certificates and CO_2 storage credits offer tradeable scheme that could drive revenue generation and be linked to the cost of storage rather than an independent carbon price.

Financial risk management

Capture and storage have substantially different financial risks and require different regulatory treatment. CO_2 capture will largely be driven by the private sector while CO_2 (transport and) storage is likely to function more like critical infrastructure – such as water, sewage, electricity and gas transmission systems. From a business model perspective, there are benefits to decoupling capture from (transport and) storage and taking a part-chain approach to development. Full-chain projects have much higher cross-chain risk, although this is substantially reduced when equity is shared by all parts of the chain. Additionally, full-chain projects do not support a multi-source to single sink model unless they plan to expand injection capacity and make it open access.

Financial risks include the uncertainty of a CO_2 supply (counterparty risk), potentially uncapped long-term liabilities, cross-chain risk, and incompatibilities between the risk appetites of the public and private sectors, along with uncertainties relating to policy and regulation. The management of financial risks depends partially on the business model developed for CO_2 storage, and partially on how CO_2 storage activities are regulated. For example, common financial risk management approaches include the availability of loan and revenue guarantees, long-term contracts, price control, public underwriting, fee regulation and insurance instruments. Different approaches can be used to address different financial risks. To account for the unique financial risks presented by CO_2 storage activities, governments could consider a system whereby storage developers are required to accept and manage business-as-usual risks, but CO_2 storage-specific risks are shared.

The leakage risk in a well-designed, correctly operated site is expected to be very low; however, the associated financial exposure is significant. Liabilities may persist for tens to hundreds of years and have the potential to persist beyond the lifetime of storage owners and operators. Uncapped liability presents an unacceptable level of risk to the private sector when not balanced by a profitable revenue stream. In the case of CO_2 storage, governments may need to bear some of the primary responsibility of certain CO_2 storage-specific risks, such as long-term liability. Regulatory frameworks should be designed to reduce the exposure of private investors without unduly exposing the public sector. They should address long-term stewardship requirements and compensatory liabilities associated with CO_2 storage sites.

Addressing long-term liability can greatly reduce future risks faced by site operators and governments. One way to do this is to implement a risk capping and duration capping mechanism in which site operators or owners would be responsible for risks below the cap, with the government taking responsibility for risks above the cap. This could cap operator-borne liabilities for certain types of leakage. Allowing the title of the storage site to be transferred to the government after a period of post-closure monitoring subject to strict performance-based conditions is another way to manage this.

CO_2 storage liabilities

Liability must be addressed early in the development of CO_2 storage-specific regulatory frameworks and business models. CCUS-related liabilities can be largely divided into three categories.

Civil liabilities are those liabilities resulting from damage caused to the interests of a third party. These are similar to the civil liabilities in major infrastructure projects, oil and gas production, and mining. Ownership of pore space and allocation of the exploitable pressure margin should be considered.

Administrative liabilities are those liabilities that may result from the exercise of a competent authority's statutory powers and may be activated in the event of environmental damage. Currently, administrative liabilities and their degree of impact are hypothetical. Existing regulation aimed at infrastructure projects, mining, and oil and gas activities can provide examples of those administrative liabilities that relate to CO_2 storage and their potential impact.

Climate liabilities are those liabilities that relate to leakage of CO_2 either in cases where an operator derived a financial benefit from storing CO_2 as part of an emissions trading system, or in cases where a penalty is assessed for a leakage due to future carbon prices or taxes. Climate liabilities are unique because they link climate change liability to financial security and they represent considerable financial risk to operators that continues even after the closure of a storage site. The financial ramifications related to future carbon prices or taxes making them unconstrained.

Some CO_2 storage liabilities will be very similar to those of other industrial activities. Others will be specific to CO_2 storage and highlight the need for tailor-made legal and regulatory frameworks. A CCUS-specific approach to the management of liability includes several critical aspects as first outlined by the IEA in 2010:

- Establishing good site characterisation selection procedures coupled with effective regulatory oversight.
- Establishing appropriate storage authorisation arrangements to ensure clear operational guidelines for operators and owners.
- Imposing ongoing performance-based monitoring and reporting requirements.
- Imposing ongoing requirements for reporting and inspection of operations to ensure problems are identified and rectified early throughout the period of operator liability.
- Incorporating a structured and well-managed process for closure, post-closure and the transfer of responsibility, including regulatory oversight of closure methods.
- Incorporating a sensible system of cost recovery and use of financial security mechanisms for handling long-term cost implications as considered appropriate within a jurisdiction.

Long-term CO_2 storage-related liabilities have been regulated in only a limited number of jurisdictions. However, government and operator treatment of storage-specific liabilities is evolving as interest in CO_2 storage grows. Further work to constrain the extent of the liabilities borne by CO_2 storage operators and to develop insurance products could facilitate storage development.

Stewardship funds and other mechanisms

Several existing CCUS-specific regulatory regimes require operators to provide some form of financial guarantee to cover the cost of long-term stewardship obligations. It may include some type of post-closure monitoring. Financial guarantees should be in place prior to any site transfer to an entity in charge of long-term stewardship and liability. Financial guarantees are often contribution-based and usually assessed on a per-unit basis during injection. Depending on the mechanism, a per-tonne fee can be paid into a post-closure trust, stewardship fund or other financial instrument.

Regulators could consider allowing third-party mechanisms to act as financial guarantees. Private mechanisms include escrow accounts, bank guarantees, performance bonds, prepaid insurance policies, corporate guarantees and third-party trust funds. Government mechanisms are also possible, including government-administered pooled funds, guarantees, indemnities or a transfer of liability from operators to a government entity.

Cost recovery and financial security mechanisms can ensure proper handling of long-term cost implications. Outlining the mechanisms that will be used in regulation can provide project developers with certainty and help them better estimate the full cost of a storage project. Some project developers suggest using a risk-weighted approach. Others recommend financial mechanisms for underwriting cashflow or liability-sharing mechanisms. Such mechanisms could reduce the risk premium that might be levied against individual projects.

Case study: A province's post-closure stewardship fund

Alberta's regulatory treatment of CCUS allows for the transfer of liability from a site owner to the state during the post-closure phase of the project. The Mines and Minerals Act states that liability is transferred upon the issuance of a closure certificate. The closure certificate is contingent on compliance with post-injection monitoring requirements, well abandonment and site decommissioning, behaviour of the CO_2 plume, and a prescribed closure period.

To finance some of the state-borne costs that will occur after title of the site is transferred, Alberta created the Post-Closure Stewardship Fund. This fund is financed by contributions from storage resource leaseholders and contributions are determined on a per-project basis.

The fund will be used to support liabilities relating to post-closure monitoring, statutory substitution liabilities and certain costs associated and orphaned sites.

Public perception

Public acceptance of CCUS technologies, especially CO_2 storage, is pivotal to the commercial rollout of CO_2 management. Public acceptance needs to be carefully managed by both governments and the private sector. As part of this, governments should work to reinforce the public's trust in regulatory agencies. In recent years, the public perception of CO_2 storage has been studied and best practices to support public engagement have been developed.

Public perception of a risk is very often greater than the statistical probability of that risk occurring and public perception can contribute to project delays and cancellations. Research suggests that there is low public awareness of CCUS, but awareness has been rising in recent years. In addition to low public awareness, CCUS technologies, including CO_2 storage, are often conflated with oil and gas activities or as a way to continue the use of coal. This does not enhance the public's perception of these technologies, and it is important to emphasise that they have far wider applications than decarbonising fossil fuels. In the case of dedicated CO_2 storage, this includes highlighting that it is not CO_2-EOR and does not result in more oil production.

Support for CO_2 storage often improves when CO_2 management is framed in the context of dealing with "waste". Significant parallels can be drawn between the waste management industry and the developing CO_2 management industry. Yet, the public has a stronger understanding of how their waste is treated than how GHG emissions are treated. Stakeholder support can improve by communicating how CO_2 management contributes to wider decarbonisation goals such as enabling negative emissions via direct air capture with storage or bioenergy with CCS (BECCS).

Successful and safe operations of storage sites contribute to mitigating public perception of risk. Project developers and operators should be transparent with regulators and local communities. This includes providing detailed information about their MMV strategy and how they will respond in the case of a risk event. Even though the probability of risk events should be very low in well-operated projects, communicating probability to local stakeholders will not necessarily assuage fears. Rather, communicating response strategies can build trust and goodwill.

Given the limited deployment of CO_2 storage infrastructure to date, regulators and developers need to be mindful of public perception. Negative occurrences, including project cancellations or risk events, more strongly influence public perception than positive occurrences or business-as-usual operations. As a result, scale-up hinges on successfully developed and safely operated projects.

Public engagement and outreach are a critical part of mitigating any risks public perception may pose to projects. Engagement strategies should be developed early during project assessment. Outreach to the local community should gradually increase through project development and continue throughout the whole project.

Actions to support deployment

Well-designed policies and private-sector support enable CO_2 storage deployment

Large-scale CO_2 management, using CCUS technologies, will require gigatonne-scale CO_2 storage along with complex, multi-modal transport networks linking CO_2 sources with sinks. For CO_2 management to realise its potential during energy transitions, urgent action needs to be taken to ensure that the availability of CO_2 storage infrastructure does not become a bottleneck. This could occur if efforts are not swiftly made to accelerate CO_2 storage resource assessment and development.

The IEA has identified five overarching categories of actions that policy makers should take to encourage CO_2 storage development:

- Identify storage resources and provide access to necessary data.
- Ensure legal and regulatory frameworks enable effective and secure CO_2 storage.
- Develop policies that support CO_2 storage.
- Support early movers and boost investment in CO_2 storage.
- Encourage the development of CO_2 storage competencies, expertise and technologies.

Public-sector actions and activities are only one part of the puzzle. The private sector can and should be involved in implementation of the above actions and take other specific steps to support CO_2 storage development such as:

- Incorporate CO_2 management into corporate decarbonisation strategies and include it in environmental, sustainability and governance (ESG) targets.
- Develop and build CO_2 storage infrastructure.[7]
- Drive investment towards CO_2 storage infrastructure by supporting CO_2 management and insuring it is permitted within sustainable finance metrics.
- Recognise proven CO_2 storage reserves as an asset.
- Create insurance products that cover CO_2 storage activities.
- Create a market for tradeable, regulation-compliant CO_2 storage certificates.

Successful development of CO_2 storage also hinges on trust in the public sector and confidence that they will appropriately manage the private-sector entities that are likely to lead the development of CO_2 storage infrastructure.

[7] This can also be done through state-owned enterprises or public–private partnerships.

Elements that feed into the commercialisation of CO_2 storage

Technical

Resource identification and assessment underpins site development. Atlases can provide the starting point for storage development in a region. Simultaneous assessment of a portfolio of sites can support build-out plans and allow resource development to proceed in a strategic and timely way.

Storage site performance will be influenced by regional subsurface activities.

Risk management processes and procedures will be refined as storage becomes more widely deployed. Sharing of good practice can contribute to improved risk management approaches.

Source–sink matching can ensure that there is rate matching between capture sites and storage sites.

Monitoring equipment should be chosen based on site needs, cost and regulatory requirements. Innovation is ongoing and can support cost reductions.

Economic

Cross-chain integration risks relate to co-ordinating market risks and the transfer of liability across the chain.

Counterparty risk can be reduced by phasing storage development and creating build-out plans. Heads of terms and other contractual relationships can provide assurance that that sufficient CO_2 will be captured to support operations.

Uncertainty surrounds business models and how the CO_2 storage sector will develop. Regional variation is likely due to differences in regulatory frameworks and market structures.

Significant pre-FID costs can make investment into storage risky for the private sector.

Cost uncertainty is likely because of the number of operating projects.

Policy

Supportive policy allocates storage-specific risks and shares risk between the public and private sectors.

Government resource management strategies help develop storage (and other) resources.

Policy needs to address carbon price uncertainty and how leakages might be treated in regimes with a carbon price.

Support for development including government-initiated pre-commercial assessments, subsidy schemes and tax incentives for CO_2 storage.

Offshore storage of imported can be unlocked by establishing bilateral agreements under the London Protocol.

Policy support across the CO_2 management value chain enables storage development.

Legal and Regulatory

Long-term liabilities are unlikely to be borne by the private sector. Regulatory frameworks should explicitly address the potential of liability transfer and conditions for transfer.

Pore space ownership should be defined and allocation of the exploitable pressure margin should be considered.

MMV requirements need to be clearly outlined.

Regulatory classification of CO_2 storage activities will influence how it develops in a given region. Regulators can consider risk- or cost-sharing mechanisms.

Licensing and permitting procedures need to be clear and transparent. Regulators should have the necessary capacity to review and process applications in a timely and consistent manner.

Identify CO_2 storage resources and provide access to necessary data

CO_2 storage resource assessment shares many similarities with the process of assessing other energy resources, but it has received less support from governments and lower engagement among the private sector. Long lead times for CO_2 storage development mean that identifying and assessing resources should be a top priority for policy makers today. Existing subsurface data can provide a valuable starting point for regional assessments.

In 2021 the US DOE and the US Geological Survey signed a memorandum of understanding to co-operate on assessing global, regional and national CO_2 storage resources. This partnership, along with the OGCI's CO_2 Storage Resource Catalogue, can help catalyse a move towards developing gigatonne-scale CO_2 storage.

Governments can play an important role in the development of storage resources by investing in pre-competitive exploration and data acquisition campaigns. They can also focus on curating and digitising existing information, such as well records, in order to make it publicly available and easily accessible.

Subsurface data collected by the private sector as part of resource exploration, development and operations are often proprietary; however, these data can be invaluable to storage resource development. Data sharing, especially of proprietary legacy data, between the public and private sector should be encouraged.

Ensure legal and regulatory frameworks account for CO_2 storage-specific needs

CCUS legal and regulatory frameworks are a key part of enabling CO_2 storage development, as is having a body or bodies dedicated to enforcing them. In consultation with the public and industry, governments should conduct a comprehensive review of existing laws and regulations that affect CO_2 storage activities. Depending on whether or not substantial regulation is already in place, governments may decide to amend existing frameworks to regulate CO_2 storage, or instead choose to develop a dedicated CCUS framework for commercial deployment. Following this, they must ensure that regulators are sufficiently staffed and have the necessary storage-related competencies and expertise to oversee the implementation of regulation. Legal and regulatory frameworks need to address several key issues:

- CO_2 storage-specific liabilities and risks
- clear and appropriate processes for issuing licences and permits
- ownership of subsurface pore space if not already defined
- site management requirements – monitoring, closure procedures, etc.

The IEA CCUS Handbook, Legal and Regulatory Frameworks for CCUS, provides an overview on how to develop appropriate frameworks. Several countries have already developed comprehensive legal and regulatory frameworks for CCUS, which form a valuable knowledge base for countries that have yet to establish a legal foundation for CO_2 storage activities.

Develop policies that support CO_2 storage

Government policies can provide strategic direction and clarity to industry. The inclusion of CCUS in national energy and climate plans, or the development of CCUS roadmaps, sends a signal that can encourage CO_2 storage development. In this regard, governments play a vital role in co-ordinating the strategic deployment of infrastructure such as CO_2 storage hubs. Including CO_2 storage resources in resource management plans can send a clear signal that they represent strategic resources that need to be developed during energy transitions.

Resource management strategies should be consistent and the government agencies that manage resources should be aligned in their treatment of CO_2 storage resources. Policy makers should consider whether existing resource prioritisation continues to be appropriate, or if it is necessary to update or redefine resource prioritisation to preserve access to CO_2 storage resources. Most jurisdictions prohibit the injection of CO_2 into oil and gas fields where there is ongoing extraction unless it is injected for the purpose of CO_2-EOR or CO_2-EGR. This can limit access to storage resources and increase development costs, and may not be technically necessary since storage operators can work to prevent hydrocarbon breakthrough. Open access to CO_2 storage should be encouraged, as should the development of multi-user sites.

Policy has a role to play in sequencing the development of CCUS activities. Resource assessment in nearly every region is required to identify CO_2 storage reserves. Without improved confidence in CO_2 storage reserves, it will be difficult to create informed development strategies for CO_2 capture and transport. Policies that support storage assessment and development directly support decarbonisation goals, and increased confidence in storage can help a country refine its energy transition pathway.

Government policies to support CO_2 storage development are also crucial to create the right market conditions that attract private-sector investment. There are a range of policy instruments that policy makers can use to incentivise CO_2 storage development and address investment challenges:

- Grants can provide capital funding to projects to conduct assessment and characterisation activities.
- Operational subsidies, such as tax credits, can provide a financial incentive per tonne of CO_2 stored.
- Tradeable certificates or obligations, such as low-carbon fuel standards, can encourage fuel producers to implement CO_2 storage.
- Innovation, R&D and deployment programmes can reduce costs.
- Risk mitigation measures, such as loan guarantees and risk capping, can provide CO_2 storage projects with enough confidence to raise debt financing from commercial lenders.
- Carbon pricing and demand-side measures can indirectly incentivise CO_2 storage development by encouraging industry to adopt emissions-reducing technologies.

Support early movers and boost investment in CO_2 storage

Economic regulation and specific policies can incentivise CO_2 storage development. This is especially true for shared infrastructure such as CO_2 transport and storage hubs. The commercialisation aspects discussed in Chapter 8 are likely to feed into the development of different business models in different regions and jurisdictions. Since there is not yet a mature business model for CO_2 storage, early movers will be the most exposed to socio-economic risks. They can be the target of dedicated incentives to stimulate investment.

Case study: Developing CO_2 storage as a regulated asset base

In 2022, as part of its Energy Security Bill, the United Kingdom took key steps to establish a framework for the economic regulation of the CO_2 management sector. In this bill, the government distinguishes between transport and storage activities and CO_2 capture activities. It establishes a regulatory framework based on a regulated asset base model. This creates revenue certainty for transport and storage service providers. Additionally, the bill outlines how financial assistance might be granted to developers of CO_2 transport and storage infrastructure.

Support the develop of CO_2 storage competencies, expertise and technologies

Energy transitions will prompt a shift away from oil and gas, which could leave regions and workers behind if not managed carefully. Since depleted oil and gas fields are a type of storage resource, there is geographic overlap with the carbon management industry. Governments can encourage the development of CO_2 storage sites in oil and gas producing regions to support continued employment and to prevent brain drain. This can support a just transition in such regions by bringing new lines of revenue and new activities. Oil and gas producing companies can encourage and support workers develop CO_2 storage related knowledge and competencies.

R&D and innovation form another area where governments can support development of CO_2 storage. The CO_2 storage assessment process can benefit from advancements made in artificial intelligence, machine learning, digitisation and legacy well assessment. Additionally, innovation in monitoring technologies can contribute to cost reductions.

CCUS centres of excellence or their equivalent can help countries develop CO_2 storage competencies and serve as a focal point for CCUS-related discussions.

Private-sector actions

The private sector has a role to play in each of the five categories of actions outlined above. In addition, there are specific actions that the private sector, either in partnership or as individual corporations, can take to support CO_2 storage deployment. Developing and building CO_2 storage infrastructure is only one small part of that.

The finance community has a major influence on ESG criteria; it can take direct steps to support CO_2 storage deployment by ensuring that investment in storage site assessment and development is considered a sustainable activity. The sustainable finance community should consider CO_2 storage as a valuable part of the decarbonisation toolkit and devote appropriate resources to it. ESG officers in corporations can encourage the inclusion of CCUS-based carbon credits in corporate carbon mitigation portfolios. ESG-based funds and activist investors can push emissions-intensive companies to capture and store their emissions to reduce them in lieu of purchasing offsets.

The insurance industry can also play a role in supporting CO_2 storage deployment. Currently, there is a very limited number of insurance products that storage operators can use. Developing such products would further de-risk CO_2 storage development.

Proven CO_2 storage reserves should be considered a valuable asset and included in corporate valuations. Consistent application of the SRMS by organisations developing storage projects can improve its visibility to the finance industry and support the valuation of storage reserves. However, accounting conventions may need to be adapted to account for specific CO_2 storage resource techniques, and a carbon price may be required to justify their value.

Case study: Assigning a book value to storage resources

On 1 November 2021 Santos and its joint venture partner Beach Energy announced that they would be investing some USD 165 million in the Moomba CCS project. Located in South Australia, commissioning is expected in 2024. To start, the project is full chain and will store 1.7 Mt/year of CO_2 sourced from the Moomba gas plant operations. However, future phases of the project will look to develop Moomba into a storage hub for the region. The project aspires to expand up to a potential injection capacity of 20 Mt a year.

To support the development of CO_2 storage at Moomba, in February 2022 Santos included 100 Mt of CO_2 storage resource capacity in its annual reserve statement. Using the SRMS classification framework, Santos assigned a book value to its storage resources in Cooper Basin.

General annex

Further reading

References are provided throughout the report as hyperlinks within the text. Additional references and further reading are provided here for readers who wish to learn more on specific topics. This list and the references within the handbook represent only a fraction of the work done on CO_2 storage to date.

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Abbreviations and acronyms

ABEX	abandonment expenditure
BECCS	bio-energy with carbon capture and storage
CAPEX	capital expenditure
CarbonSAFE	Carbon Storage Assurance Facility Enterprise
CCS	carbon capture and storage
CCUS	carbon capture, utilisation and storage
CO_2	carbon dioxide
CSLF	Carbon Sequestration Leadership Forum
DAC	direct air capture
DACS	direct air capture with storage
DOE	Department of Energy
EGR	enhanced gas recovery
EMDE	emerging market and developing economies
EOR	enhanced oil recovery
ESG	environmental, social and governance
EWR	enhanced water recovery
FEED	front-end engineering design
FEP	features, events and processes
FID	final investment decision
GHG	greenhouse gas
IEAGHG	IEA Greenhouse Gas R&D Programme
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LNG	liquid natural gas
MMV	measurement, monitoring and verification
OGCI	Oil and Gas Climate Initiative
OPEX	operational expenditure
PC	post closure
PRMS	Petroleum Resource Management System
R&D	research and development
SOE	state-owned enterprise
SPE	Society of Petroleum Engineers
SPV	special purpose vehicle
SRL	storage readiness level
SRMS	Storage Resource Management System
TRL	technology readiness level

Units of measure

Mt	megatonne
kt	kilotonne
Gt	gigatonne
t	tonne
m	metre
M_L	local magnitude scale
M_w	moment magnitude scale
MJMA	Japanese Meteorological Agency Magnitude Scale

Glossary

Abandoned well:	A well that is no longer used for extraction and has been closed following plug and abandon procedures. Sometimes this refers to a well that is no longer active but is not properly closed.
Appraisal:	The phase following exploration when an identified resource is studied in depth to determine its size and how to develop it most effectively.
Bankable capacity:	An economic risked practical capacity that is matched to emitting sources at a level suitable for FID.
Basalt:	A dark fine-grained volcanic rock.
Baseline survey:	The collection of storage site data before injection commences, to help identify any possible effects of storage during or after injection.
Bicarbonate (HCO_3^-):	One of two forms that CO_2 takes when it dissolves in water.
Booked resource:	A proven reserve that has been assigned an asset value and included in a company's asset reporting.
Borehole:	A deep hole in the ground, usually made via drilling.
Brine:	A highly concentrated salty water.
Brine extraction well:	A well used to extract (or produce) brine from a reservoir.
Brownfield:	Denotes a site that has previously been developed.
Capacity:	General definition: The estimated storable capacity of a resource. SRMS definition: The estimated commercially storable quantity of CO_2 for a given resource/project.
Caprock:	A harder or more resistant rock type that sits above a reservoir. Caprocks are impermeable and act as seals.
Carbonate minerals:	Minerals that contain carbonate ions.

Carbonic acid (H_2CO_3):	A weak acid formed when CO_2 dissolves in water.
Casing (or casing string):	Large diameter pipes that are inserted into wells/boreholes to keep them open and to isolate the well from surrounding rock, and the surface .
Casing shoe:	The bottom of a string of casing.
Closure period:	The period between cessation of injection activities at a storage site and the granting by the relevant authority of a closure authorisation for the storage site.
CO_2 plume:	See Plume.
CO_2 storage resources:	Permeable rock formations with pores that can be filled with CO_2.
CO_2 stream:	CO_2 and other allowed substances injected into a storage site.
Coal:	A solid, combustible fossil sedimentary rock. Coal comes from buried vegetation transformed by the action of strong pressure and high temperatures over millions of years.
Coal seam:	A bed of coal.
Conformance	How well the actual behaviour of injected CO_2 aligns with modelled behaviour.
Connectivity:	The degree to which matter, such as water or CO_2, can move between different parts of a system.
Containment:	The features and processes that keep CO_2 within a store for a specific period of time.
Decommissioning:	The dismantling and removal of injection facilities following cessation of injection activities at a storage site and the restoration of a storage site as required by the relevant authority prior to the granting by the relevant authority of a closure authorisation.
Dedicated CO_2 storage:	Storage of CO_2 in geological formations.
Depleted oil or gas field:	An oil or gas field that has reached the end of its producible life.
Dynamic capacity:	A deterministic estimation made from dynamic simulations.
Effective capacity:	A capacity estimation based on the amount of theoretical capacity that can be

	accessed and meets necessary geological and engineering criteria.
Enhanced gas recovery:	Extraction of natural gas that cannot be produced or recovered through conventional means.
Enhanced oil recovery:	Also known as tertiary recovery, the injection of fluids (such as water, CO_2 or other chemicals) to enhance productivity of a field and recover oil that would normally be irrecoverable otherwise.
Enhanced resource recovery:	The process through which CO_2 is used to enhance the production of another resource such as water, natural gas or oil.
Enhanced water recovery:	Extraction of formation water to relieve pressure in a reservoir. Extracted waters need to be treated before they are considered potable.
Exploration:	The process of searching for and identifying deposits of natural resources.
Exploration well:	A well used to characterise storage resources including their capacity, containing features and performance.
Extraction well:	See Production well.
Fault:	A break or flat surface in a rock across which observable displacement is visible.
Field:	An accumulation, pool or group of pools of natural resources in the subsurface. An oil or gas field consists of one or more reservoirs in which hydrocarbons have been trapped by a caprock.
Formation:	A body of rock that is distinct and continuous to allow its mapping. A formation is a fundamental unit in stratigraphy.
Fracture:	A crack or break within a rock. If displacement is visible on either side of the break, then it is a fault rather than a fracture.
Fracture pressure:	The pressure required to break a reservoir or seal.
Geological formation:	See Formation.
Geological unit:	See Unit.
Greenfield:	Undeveloped sites, potentially not previously explored.

Injection facilities: The surface installations required to undertake injection activities at a storage site.

Injection rate: The rate at which CO_2 (or another substance) is injected into a reservoir.

Injection rate decline: The rate at which injectivity declines.

Injection well: Wells used to inject CO_2 or other fluids.

Injectivity: The ability to inject CO_2 (or another substance) into a reservoir at a required rate over time.

Japanese Meteorological Agency Magnitude Scale (M_{JMA}): A calculated scale based on the maximum amplitude of ground motion used in Japan.

Lead: A subsurface feature that has the potential to trap oil, gas or CO_2. Will typically contain multiple prospects.

Leak: CO_2 being released from the storage complex in an unintended manner.

Leakage: The unintended release of CO_2 from the storage complex.

Legacy well: A previously drilled well in a region or area. It can be actively producing, abandoned, orphaned or in an unknown state.

Limestone: A hard calcium carbonate rich sedimentary rock often used as a building material.

Local magnitude scale (M_L): Commonly known as the Richter scale. Based on the maximum amplitude of ground shaking.

Logging: The process of making a detailed record of well features and the different formations the well crosses. Can be done on cores from the well and by lowering instruments down the well to take measurements.

Mafic: Igneous rocks rich in magnesium and iron. Basalts are mafic rocks and peridotites are ultramafic.

Magnitude: The overall strength or size of an earthquake.

Matched capacity: An economic risked practical capacity that is matched to emitting sources.

Measurement, monitoring and verification (MMV):	Plans and procedures for measuring reservoir properties and injected CO_2, monitoring how the reservoir and injected CO_2 behaves, and verifying that behaviour is in line with what is expected. Also known as monitoring, reporting and verification (MRV).
Microseismicity:	Faint Earth movement.
Migration:	The movement of CO_2 within the storage complex.
Mineral trapping:	When dissolved CO_2 reacts with minerals in the reservoir to form solid minerals.
Mineralisation of CO_2:	The process during which CO_2 reacts with metal oxides to produce minerals.
Moment magnitude scale (M_w):	Measurement of an earthquake's magnitude based on its seismic moment. It is the authoritative magnitude scale for earthquake ranking. Small earthquakes will have a similar magnitude on this scale and the local magnitude scale.
Monitorability:	The ability to monitor a CO_2 storage site.
Monitoring well:	Wells outfitted with the equipment needed to monitor injected CO_2, the reservoir and the CO_2 plume.
Mudstone:	A sedimentary rock formed from compacted mud and predominately composed of clay minerals. Lacks the laminations of shales.
Operator:	The holder or holders of an exploration authorisation or a storage authorisation for a storage site.
Orphaned well:	A well whose ownership cannot be determined. Usually, orphaned wells are not plugged or sealed properly.
Overburden:	The geological matter between the storage complex and the surface projection of the storage complex.
Peridotite:	A dark coarse-grained igneous rock composed mainly of magnesium-rich silicate minerals.
Permeability:	How easily a fluid can pass through a material.

Permit: An official written statement that permits an activity. In some jurisdictions it may be called a licence.

Play: A group of resource prospects in the same region that have the same geological history.

Plug and abandon: The process to prepare a well for permanent closure. Cement plugs are installed in the well at specific intervals to isolate different geological layers. After the well top is removed and the area remediated.

Plume: The volume of CO_2 dispersing or dispersed in the subsurface.

Pool: An accumulation of hydrocarbons in a reservoir.

Pore space: The free space between mineral grains.

Porosity: The proportion of rock pores compared to the total rock volume.

Post-closure: The period from the granting by the relevant authority of a closure authorisation.

Practical capacity: A capacity estimation that accounts for technical, legal and regulatory, and infrastructure requirements and restrictions.

Pre-competitive exploration: The phase of exploration that typically does not require permits and rarely involves physical interventions such as drilling.

Production well: A well used to recover (extract) a liquid or gas resource from the subsurface. A production well can be for oil, natural gas, water or other resources.

Project period: The exploration period, operation period and closure period.

Prospect: An area with a probable economic quantity of a resource (e.g. oil, gas, minerals or storage resource).

Relative permeability: The ability of two or more fluids to pass through a rock.

Reserves: Known quantities of a commodity that are commercially recoverable.

Reservoir: Permeable and porous subsurface rock formation found both onshore and offshore.

Reservoir fluids: The pressurised substances within a reservoir which can flow or move through it.

Reservoir pressure: The pressure of fluid within the pores of the reservoir.

Residual trapping: The trapping of CO_2 in small pores by physical (capillary) forces.

Resources: Estimated amounts of a geological commodity in a given geographic area.

Risk assessment: The process of risk identification, risk analysis and risk evaluation.

Saline aquifer: Porous and permeable sedimentary rocks that contain salty, non-potable water commonly known as brine.

Sandstone: A sedimentary rock formed of sand, quartz and other mineral grains that have been cemented together.

Seal: A feature such as a fault or caprock that prevents reservoir fluids from passing through it.

Sedimentary basin: Geographic regions where thick layers of sediment have accumulated.

Sedimentary rock: One of the three primary rock types. Formed when material is deposited and then compacted at or near the Earth's surface and when minerals are precipitated at normal surface temperatures.

Seismicity: The spatial and temporal distribution of earthquakes and their magnitudes.

Shale: A layered sedimentary rock formed from mud and clays.

Siltstone: A fine-grained sedimentary rock formed from silt.

Solubility trapping: When CO_2 dissolves into formation fluids causing it to be trapped by geochemical means.

Source-sink matching: The process by which sources of CO_2 such as emissions points are associated with CO_2 storage resources. There are

	various ways to conduct source-sink matching.
Static capacity:	A probabilistic estimation that accounts for uncertainties such as reservoir quality.
Storage complex:	The primary containment system and any secondary containment systems.
Storage efficiency:	The proportion of pore space within a targeted reservoir that can be filled with CO_2. Roughly equivalent to the term "recovery factor" used by the oil and gas sector.
Storage site:	The storage complex, overburden and the surface projection of the storage complex and injection facilities.
Store:	See Storage complex.
Stratigraphic trapping:	See Structural trapping.
Stratigraphy:	The classification of different layers of rocks.
Structural trapping:	The trapping of CO_2 in a reservoir via impermeable boundaries such as a caprock.
Supercritical CO_2:	The state of CO_2 when it is at or above its critical temperature and critical pressure.
Theoretical capacity:	A regional or national first approximation of storage resource capacity.
Tubular:	A term used to refer to the pipes and tubes used by the oil and gas industry.
Ultramafic:	Igneous rocks with a very high percentage of dark coloured minerals high in magnesium and iron. The main rock type found in the Earth's mantle.
Unintended migration:	Migration of the CO_2 plume in a direction different to planned or beyond the expected/modelled boundaries.
Unit:	A volume of rock with defined and identifiable characteristics.
Well:	A deep hole in the ground, usually made via drilling.
Well abandonment:	See Plug and abandon.
Well completion:	The process during which a drilled well is prepared for its activity.
Wellbore:	The actual hole that forms the well.

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