CCS Wells Technology Roadmap

In Partnership with
North Sea Transition Authority

DNV

Net Zero Technology Centre
Technology Driving Transition

North Sea Transition Authority

Within the UK there is an abundance of knowledge of drilling, operating and abandoning wells from the oil and gas industry. Much of this knowledge and associated technologies can be transferred to the CCS industry. However, it must be noted that there are numerous unique challenges associated with CCS wells which require technology and deployment methodology adaptation and, in some cases, completely new solutions.

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Executive Summary

Carbon Capture and Storage (CCS) plays a key role in the UK reaching its net zero target by 2050. Ensuring the long-term containment of CO_2 is essential for the CCS industry's success, with wells serving as a vital element in both the storage operation and the integrity and monitoring of storage sites.

The UK North Sea offers substantial storage potential and there are currently 27 CO_2 appraisal and storage licences on the UK Continental Shelf (UKCS)[1]. With its long and successful history in well lifecycle operations offshore within the oil and gas industry, the UK is well positioned to transfer tools, technologies and expertise from the oil and gas industry to the emerging CCS industry, however it must be recognised that CCS wells present their own unique challenges.

This CCS Wells Technology Roadmap, developed by the Net Zero Technology Centre (NZTC) and DNV for the North Sea Transition Authority (NSTA), serves as an industry resource to raise awareness of deployable technologies capable of addressing the challenges posed by CCS wells. Additionally, technology gaps and challenges not yet addressed are detailed, with emerging solutions and areas for future technological advancement highlighted. The topic areas relevant to CCS wells that this technology roadmap addresses are: Materials and Equipment, Intervention and Workovers, and Monitoring.

CCS wells require carefully selected materials and equipment to withstand challenging conditions, such as corrosion, thermal and pressure cycling, rapid phase changes and extreme cold, which may be experienced over the life of the well and post-operation abandonment. Advanced materials including corrosion-resistant alloys and specialised cements are available and work is ongoing to validate and qualify equipment, much of which is transferred from the oil and gas industry, for use in the CO_2-rich environment within which CCS wells will need to operate. Industry collaboration, such as through joint industry projects, is helping drive the standardisation and qualification of materials and equipment.

Intervening and performing workovers on CCS wells face the challenge of the presence of CO_2 or CO_2-enriched fluids in the well. Again, while much of the equipment used is similar to conventional oil and gas operations, additional validation and risk management is necessary to ensure safe and effective well maintenance, with industry experience in this area still developing. Well control and CO_2 handling for CCS wells is particularly important and an area where potential gaps exist, however technological solutions are emerging in this space.

Regarding monitoring, a variety of advanced technologies are commercially available and emerging to support robust well monitoring for CCS projects, ensuring that CO_2 remains securely stored and regulatory obligations are met. These include high-resolution sensors and gauges, fibre-optic systems, wireless telemetry, and tracer technologies for real-time detection of leaks, verification of well integrity, and to monitor CO_2 injection and track plume movement. The main challenge is achieving an optimal balance between comprehensive monitoring and cost-effectiveness, supporting safe and long-term storage in alignment with the economic realities of CCS operations.

In addition to the aforementioned topic areas related to CCS wells, legacy oil and gas wells, if located within a CCS storage complex or in pressure communication, have the potential to act as leak pathways and therefore pose a significant threat to the secure storage of CO_2 if their integrity is compromised or they have not been abandoned to appropriate standards. For this reason, remediation technologies for legacy oil and gas wells have also been addressed within this roadmap, with a specific focus on well re-entry.

[1] Carbon Capture and Storage - The Move to Net Zero - The North Sea Transitioning Authority

Many technologies required for CCS well activities already exist within the oil and gas industry but require adaptation and validation to ensure suitability. As the CCS industry develops and data availability increases the industry will be able to advance its understanding of CO_2 behaviour and operational envelopes assisting in advising adaptation requirements and standardisation opportunities. Standardisation in the well basis of design, testing procedures and qualification protocols have the potential to reduce costs which, in an industry with a challenging economic landscape, is vital. It should also be noted that, due to the infancy of the CCS industry, unforeseen challenges are likely to be encountered which will require future technological advancements. The CCS industry, with transferrable technologies and expertise from the oil and gas industry, will be well placed to deliver these.

"Successful carbon storage is critical to the future of the CCS industry – and that starts with wells that are safe, reliable and built to last.

The UK's strong track record in oil and gas well operations provides a solid foundation, but CO_2 storage presents unique technical challenges that demand adaptation and innovation. This roadmap demonstrates how combining expertise with technology innovation can overcome these challenges, ensuring reliability and integrity in carbon storage projects across the North Sea and beyond.

We appreciate our industry partners' insights and collaboration – continued knowledge-sharing and collaboration are vital to advancing CCS at the necessary scale and pace."

Catherine Sherwin, Technology Manager
Net Zero Technology Centre

"Developing a robust carbon storage well infrastructure is critical to unlocking the full potential of the UK's CO_2 storage capacity. This roadmap provides industry with a clear view of the technologies needed to deliver safe, efficient, and long-term storage- supporting our transition to net zero and enabling progress across the licensed storage sites."

Keith Hogg, Wells Manager
North Sea Transition Authority

"Ensuring the integrity of CO_2 storage wells is not just a technical requirement, but the foundation upon which the success of carbon capture and storage rests. Drawing upon decades of operational expertise and world-leading oil and gas practices, this report demonstrates and provides confidence that as an emerging industry we are poised to deliver safe, reliable, and long-term solutions for CO_2 containment, securing a cleaner future for generations to come."

Iain Martin, CCUS Technology Manager
Net Zero Technology Centre

"DNV believes that Carbon Capture and Storage (CCS) is at a turning point, with a number of upcoming projects growing significantly and with operational capacity increasing substantially in the near future. We hope this technology report on CCS Wells will help in de-risking and improving projects in the United Kingdom and beyond in a safe and reliable way, along with meeting net zero targets and making the UK the leader in CCS."

Zilvinas Petrauskas, Senior Engineer
DNV UK Limited

Initiative Overview

In early 2025 the NSTA commissioned the NZTC and DNV to develop this CCS Wells Technology Roadmap. The purpose of this roadmap is to identify existing and emerging technologies for CCS wells offshore UK, with the aim of providing a resource for industry to use during the development of their CCS projects. Appropriate technology selection will play a big part in the success of future CO_2 storage projects helping to ensure long term environmental safety, fostering public confidence and assisting in gaining regulatory approval.

Within the UK there is an abundance of knowledge of drilling, operating and abandoning wells from the oil and gas industry. Much of this knowledge and associated technologies can be transferred to the CCS industry. However, it must be noted that there are numerous unique challenges associated with CCS wells which require technology and deployment methodology adaptation and, in some cases, completely new solutions. These challenges and differences to oil and gas wells are discussed throughout the report and appropriate technology solutions explored. In addition, technology gaps and challenges not yet addressed are detailed and emerging solutions and areas for future technological advancement highlighted.

The roadmap has been developed over a number of months, initially defining the topics to be addressed: Materials & Equipment, Intervention & Workovers, and Monitoring. During the define stage, the importance of technologies for remediating legacy oil and gas wells was apparent and therefore this has also been included as a fourth topic. Industry engagement was the next step and a crucial part of the roadmap development. NZTC and DNV engaged with numerous operators and supply chain companies, both locally and internationally, through engagement workshops and interviews respectively. These sessions were used to gain insights into available and emerging technology solutions; successful, or otherwise, deployments of technology on active CCS and CO_2 enhanced oil recovery (EOR) developments; current and future challenge areas; and technology gaps where further work may be required. Information gathered through the industry engagement has proven invaluable and has been utilised throughout the roadmap. Finally, technologies within the four topic areas mentioned above and suitable for addressing challenges raised during industry engagement, were researched, assessed and shortlisted for inclusion in the roadmap. **Note: The roadmap does not contain an exhaustive list of all technologies but rather a selection of some of those existing and emerging.** Inclusion in this roadmap does not represent NSTA's, NZTC's or DNV's view on which technologies should be deployed. The technologies listed in this roadmap are provided as references. Operators and project developers should always perform their own technology search and due diligence when selecting the most appropriate technologies for their projects.

This roadmap has been split into the four key topic areas each with its own sub-categories as shown in figure 2. Within each section, background information is provided on the topic area highlighting the difference to oil and gas and the challenges associated with CCS Wells. Technology profile boxes are incorporated detailing relevant existing and emerging technologies. Finally, technology gaps and areas for research and development (R&D) are identified. The technology profile boxes throughout the report show the technology name, provider name, a description of the technology, status and website link. All technologies included are summarised in tables 1 - 4. It should be noted that for many the status is "commercially available" having been developed for the oil and gas industry. Due to the infancy of the CCS industry not all technologies will have been installed in active CCS wells and this should be taken into account by the reader. Where possible, information on use in CCS wells or specific testing for CCS has been provided. Again, operators' due diligence and project optimisation should always be performed before selecting technologies.

An additional challenge of the infancy of the CCS industry is surrounding industry guidance and regulation. This is addressed first prior to delving in to each of the four key topic areas.

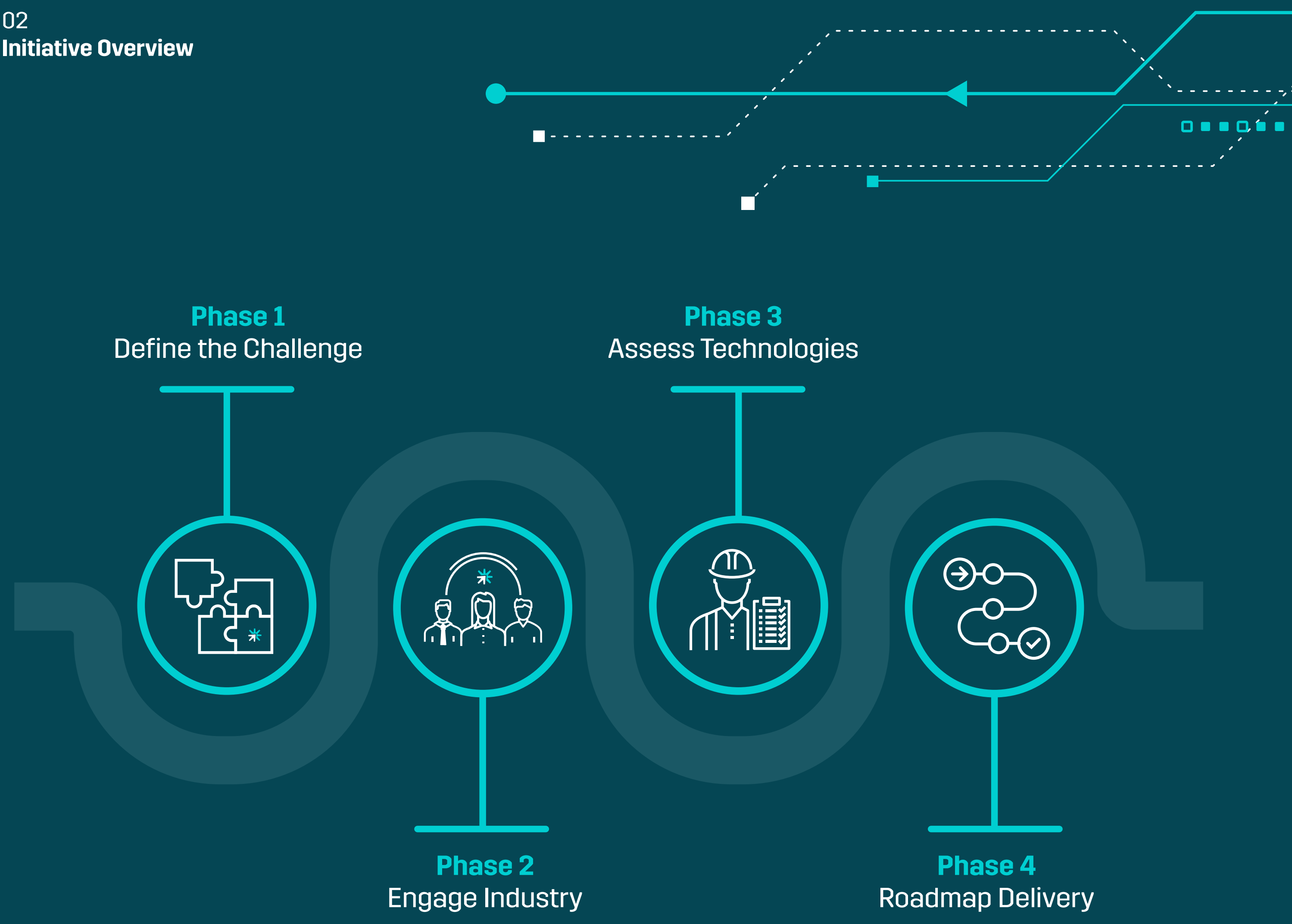

Figure 1. CCS wells technology roadmap development process

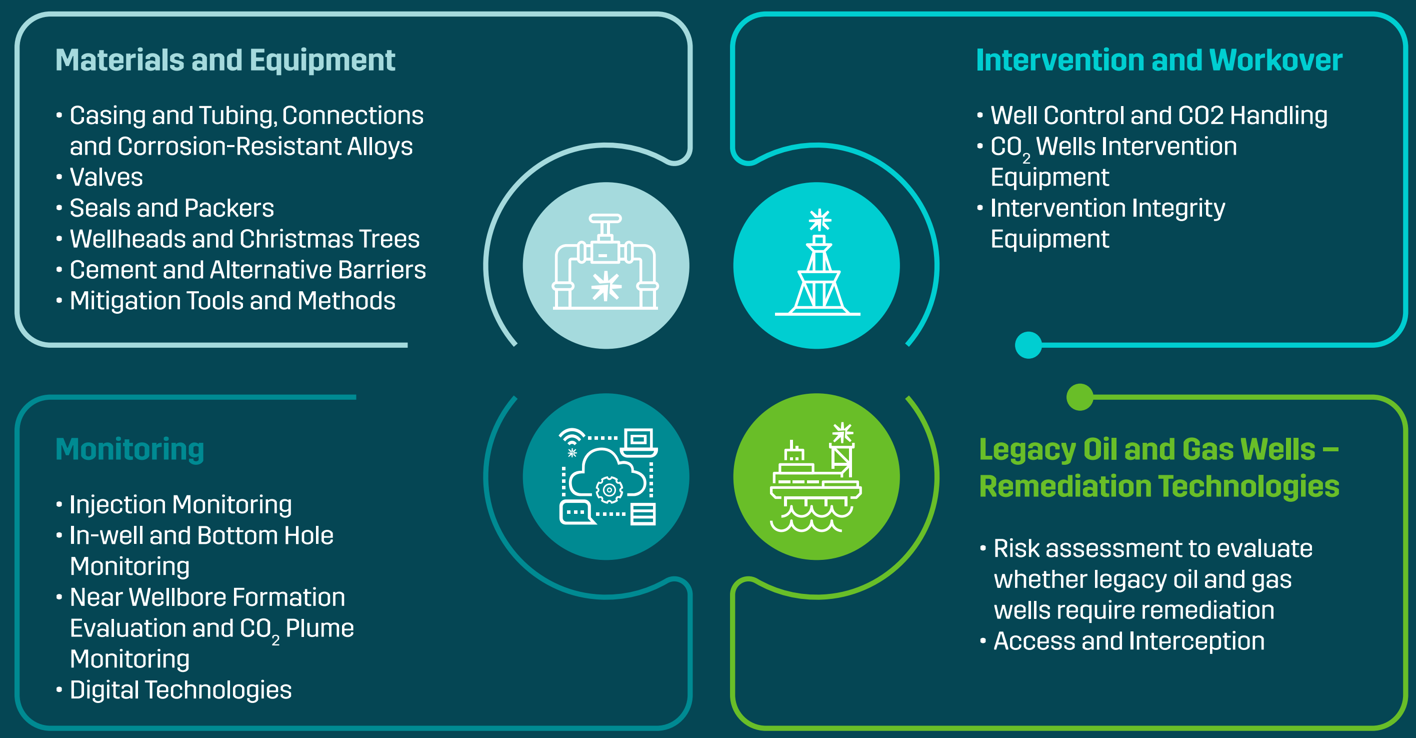

Figure 2. Roadmap topic areas and sub-categories

Materials and Equipment

	Wood. et al. - Industry Guidelines for Setting the CO_2 Specification in CCUS Chains (JIP)
Casing and Tubing, Connections and Corrosion-Resistant Alloys	Composite Lining Systems (CLS) - GlassBore®
	Composite Lining Systems (CLS) - GlassWrap®
	Corrosion Resistant Alloys (CRA) - Casing and Tubing for CO_2 wells
	CRA Tubulars - Titanium-Lined Composite Tubulars (TCT)
	DNV et al. - Materials performance in CCS Wells Joint Industry Project (JIP)
	MaxTube - Duoline® 20 - fibreglass lined tubing
	Nippon Steel - Casing and Tubing for CO_2 wells
	NOV - Tuboscope™ TK™-Liner
	Tenaris - TenarisHydril Blue® Dopeless® 3.0 premium connection
	Vallourec - Glass Reinforced Epoxy (GRE) liners
	Vallourec - VAM® 21 CLEANWELL®
Valves	Baker Hughes - Thunder™ Tubing-Retrievable Subsurface Safety Valve (TRSSV)
	Halliburton - NeoStar™ CS tubing retrievable safety valve (TRSV)
	NZTC et al. - Subsurface Safety Valve (SSSV) for CCS
	SLB - TRMAXX™ 5E & SlimTech™ Valve - Surface-Controlled subsurface safety valves
	Weatherford - Optimax™ Series Safety Valves
Seals and Packers	Baker Hughes - Aptum™ seals and Premier™ NXT Packers
	NZTC - Shear-Seals JIP
	Welltec - Welltec® Annular barrier (WAB®)
Wellheads and Christmas Trees	Baker Hughes - CCS Wellhead Solutions
	SLB - OneSubsea - CCS Christmas Tree Solutions
Cement and Alternative Barriers	Baker Hughes - PermaSet cement system
	Halliburton - CorrosaCem™ & CorrosaLock™
	SLB - EverCRETE™
Mitigation Tools and Methods	Expro - Collar Load Support (CLS)™ System and Fluid Grip Tong®

Table 1. Materials and equipment technologies

Intervention and Workover

Well Control and CO_2 Handling	Aquaterra Energy - AQC-CW well access solution
	Aquaterra Energy - Sea Swift CO_2 Platform Solution
	Moss Maritime - Moss CS ECO-X™
	Noble - Modular CO_2 Handling Package
CO_2 Wells Intervention Equipment	CORETRAX – An Expro Company - Reline – expandable casing & tubular patches
	dti - M-Bubble Sealing Solutions
	Expro - Octopoda
Intervention Integrity Equipment	SLB - Epilogue
	SLB - PowerFlex/PowerEcho – Annular barrier evaluation service
	Weatherford - SecureView® - Cased hole well integrity monitoring

Table 2. Intervention and workover technologies

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Initiative Overview

Monitoring

Injection Monitoring	Solartron ISA/Ametek - Carbonstream Subsea and Topside CO_2 Flow Meter
In-well and Bottom Hole Monitoring	Acoustic Data - SonicGauge
	Aquaterra Energy - CO_2 monitoring platform
	Baker Hughes - SureVIEW CoreBright optical fibre
	Cereus Energy Ultrasonics - Nusonix
	Emerson - Roxar™ Downhole Wireless System
	Expro - CaTS EMX wireless monitoring system
	Expro - Distributed Fibre Optic Sensing (DFOS)
	Halliburton - DataSphere® Array and DataSphere® Opsis
	Halliburton - DataSphere® LinX Monitoring System
	Metrol - Paragon EM
	Sentinel Subsea - WellSentinel
	Silixa - Carina CarbonSecure
	SLB - Metris Eclipse
	SLB - Metris Evolve/Extreme/Express
	SLB - WellWatcher Neon
	Weatherford - ForeSite Sense
	WellSense - Fli Dynamic De-Spool Probe
Nearwellbore formation evaluation and CO2 Plume Monitoring	QuantumPro Inc - FloTrac™
	Resman Energy Technology - High Integrity Detection System (HIDs)
	SLB - CCS Real-Time Induced Seismicity Monitoring (RT-ISM)
	SLB - Optiq and Optiq Seismic
	SLB - Pulsar
	Weatherford - Raptor 2.0
Digital Technologies	Baker Hughes - CarbonEdge
	Halliburton - CO_2 Storage Suite
	Halliburton - Visum® CS MMV Service
	Heriot Watt - A Risk-Based Modelling Framework for Assessing Legacy Well Integrity in CCS
	Net-Zero Geosystems - DRISCO$_2$Well
	Peloton Well Focused - Peloton Platform Well Integrity

Table 3. Monitoring technologies

Legacy Oil and Gas Wells - Remediation Technologies

Access and Interception	Aquaterra Energy - Recoverable Abandonment Frame (RAF)
	Halliburton - WellSpot® Active Magnetic Ranging Service
	SLB - Well Radar™
	Wild Well Control - Engineering and optimisation – Relief Wells

Table 4. Legacy oil and gas wells - remediation technologies

Existing Industry Guidance and Regulation

CCS wells are generally designed and constructed using components and well barrier principles similar to oil and gas wells. As such, the rules, regulations and international guidance and standards for CCS wells are also based on the industry experience and technical expertise from the oil and gas industry. Specific regulations for CCS wells are available in the UK and industry guidance, and standards are available in the form of ISO, IOGP and DNV standards, guidelines and recommended practices. Additionally, technical and academic papers and benchmarking gap studies are available covering detailed technical topics for CCS wells. Table 5 summarises key standards and their applicability to CCS wells.

Key Standard	Type	Maintained by	Applicability to CCS Wells	Link
Guidance on Applications for a Carbon Storage Permit	Guidelines	NSTA	Provides guidance on the requirements for CCS wells, and associated information requested, when applying for a carbon storage permit.	Guidance on Applications for a Carbon Storage Permit
DNV-RP-J203 Geological Storage of carbon dioxide (aligned with ISO 27914)	Recommended Practice (RP)	DNV	Includes recommended practices for measurement, monitoring, and verification (MMV) and defines performance requirements and procedures for a number of topics including well assessment and management planning.	DNV-RP-J203 Geological storage of carbon dioxide
Well Decommissioning for CO_2 Storage	Guidelines	OEUK	Provide industry recommendations and good practice for well decommissioning for CO_2 storage. Supplementary to OEUK Well Decommissioning Guidelines Issue 7.	OEUK Well Decommissioning for CO2 Storage Guidelines
ISO 27914:2017 - Carbon dioxide capture, transportation and geological storage — Geological storage	International Standard	ISO	Establishes requirements and recommendations for the geological storage of CO_2. It covers both onshore and offshore sites and addresses well infrastructure, development, integrity, operation, maintenance, recompletion, abandonment, and monitoring throughout the entire life cycle of CCS wells—from site screening and selection to post-injection closure.	ISO 27914:2017 - Carbon dioxide capture, transportation and geological storage — Geological storage
NORSOK D-010 - Well integrity in drilling and well operations	Standard	Norwegian Petroleum Industry / Standards Norway	Defines requirements and guidelines relating to well integrity in drilling and well activities. Used to guide CO_2 storage well development, inc. well construction material, and operation in the Norwegian Continental shelf (Sleipner & Snøhvit).	Standard Norge | standard.no. NORSOK D-010:2021+AC:2024
IOGP Report 676 - Well abandonment and integrity evaluation for CO_2 storage	Guidelines	IOGP	Provides guidelines and considerations for well plugging and abandonment approaches of both project and legacy wells within a CO_2 storage site. It includes well integrity evaluation methods, barrier philosophy and plugging materials.	Well abandonment and integrity evaluation for CO2 storage | IOGP Publications library
EPA Class VI Guidance Documents	Guidelines	EPA	Numerous guidelines including ones covering well construction, testing, monitoring and plugging	Final Class VI Guidance Documents | US EPA

Table 5. Key standards and their applicability to CCS wells

CCS on the UKCS is regulated under the Energy Act 2008, which establishes the licensing framework for CO_2 storage in the UK. The NSTA serves as the Competent Authority for licensing offshore storage sites and associated pipelines. However, within the territorial waters adjacent to Scotland, licensing authority rests with the Scottish Ministers. In addition, developers must secure the necessary rights from The Crown Estate or Crown Estate Scotland to proceed with storage projects.

Environmental compliance is overseen by the Offshore Petroleum Regulator for Environment and Decommissioning (OPRED), under the Offshore Environmental Impact Assessment (EIA) Regulations 2020. While the International Maritime Organisation's London Protocol has implications for cross-border CO_2 transport and storage, it is referenced here for context only, as this roadmap focuses specifically on the UKCS.

The Department for Energy Security and Net Zero (DESNZ) leads the UK Government's policy and funding initiatives for CCS, aiming to support the country's target of achieving net zero emissions by 2050.

CO_2 storage has been operational in the Norwegian Continental Shelf since 1996, beginning with the Sleipner field, which injected CO_2 extracted from produced gas. The Snøhvit project followed in 2008. These projects have been extensively studied in academic literature, particularly regarding well construction materials guided by NORSOK D-010 standards and early experiences in CO_2 plume monitoring which were developed before formal monitoring guidelines were established.

Recommended practices for measurement, monitoring, and verification (MMV) are outlined in DNV-RP-J203 (aligned with ISO 27914), which provides a structured approach to selecting, qualifying, and managing geological CO_2 storage sites. Additionally, DNV-SE-0473 offers certification standards for such sites and projects.

In the UK in particular, Offshore Energies UK (OEUK) Guidelines for Well Decommissioning for CO_2 Storage (Issue 1) were developed to assist well operators and engineers in ensuring that decommissioned wells maintain integrity for future CO_2 storage. These guidelines are intended to complement the broader OEUK Well Decommissioning Guidelines (Issue 7).

Internationally, ISO 27914[2] is the key standard for CO_2 storage wells, where other industry guidelines, such as the International Oil and Gas Producers (IOGP) Report 676[3] "Well abandonment and integrity evaluation for CO_2 storage", provide technical guidance on CO_2 legacy, injection and storage wells. Numerous detailed studies have been performed, including IAEGHG Technical Report 2018-08[4], "Well engineering and Injection Regularity in CO_2 storage wells," SINTEF Report 2024:00065[5] "CCS Well Design Requirements" and Havtil's commissioned report from Wild Well Control 2024-380[6], "CO_2 blowout considerations", all of which provide insightful detailed considerations to CO_2 well design, operation and integrity management. The report, "Deep geological storage of carbon dioxide (CO_2), offshore UK: containment certainty[7]" addresses CCS wells and risks surrounding well integrity and containment assurance. Additionally, several international work groups, such as the American Petroleum Institute (API), OEUK, Norwegian wells forum, Society of Petroleum Engineers (SPE) and others have formed work groups and joint industry projects (JIPs) to study CCS wells. Outcomes of some of these work groups and JIPs are driving updates to current standards and guidelines.

[2] ISO 27914:2017 Carbon dioxide capture, transportation and geological storage — Geological storage
[3] IOGP Report 676 Well abandonment and integrity evaluation for CO_2 storage
[4] IEAGHG, "Well Engineering and Injection Regularity in CO_2 Storage Wells", 2018-08, November 2018.
[5] SINTEF Report 024:00065 "CCS Well Design Requirements"
[6] Havtil / Wild Well Control, "CO_2 blowout considerations"
[7] Daniels, et. Al. "Deep geological storage of carbon dioxide (CO_2), offshore UK: containment certainty"

03
Existing Industry Guidance and Regulation

CCS Wells Technologies

Technologies for CCS wells have some unique challenges to overcome when compared to oil and gas operations. Learnings can be taken from currently active CCS storage sites and from CO_2 EOR, particularly prevalent in the US. However, the same track record, knowledge base, data, guidelines and standards that there is for oil and gas does not yet exist for the CCS industry meaning that appropriate technology selection requires additional due diligence. Learnings from active CCS projects also confirms that although many of the tools and methods used for work such as drilling and petrophysical modelling are similar in both the oil and gas and CCS industry, there are key differences that need to be understood when applying oil and gas methodology and tools to CCS projects.[8] Ceyhan et al. 2022[9] stated that "the differences between CCS wells and conventional oil and gas wells require a different approach to well design" and that "If CCS wells were to be designed using conventional methods, the wells might fail to maintain their integrity, thus resulting in the failure to contain injected CO_2 in the sequestration zone."

The above-mentioned papers ([8&9]) provide detailed overviews of the difference of CCS and oil and gas wells. Table 6 below summarises key differences which should be considered in the well design for CCS wells.

An additional key aspect to be taken into consideration for CCS projects as a whole is the socio-economic drivers. Oil and gas developments are driven by profitable economics with the "social licence to operate" gained from clean and safe production and the delivery of reliable and relatively cheap energy. CCS projects have different socio-economic drivers such as assisting in meeting national and global emissions reduction targets, decarbonising industrial emitters and availability of green financing schemes including operational subsidies[8]. Due to the different economic landscapes surrounding oil and gas and CCS wells, one of the key challenges is to reduce the costs related to CCS wells, some of which could come from technological advancements. However, it should also be noted that many of the differences described in Table 1 come at cost premiums, such as specialist materials to address the corrosion risk and additional monitoring technologies. Therefore, a balance needs to be drawn between delivering a safe and effective well fulfilling all measurement, monitoring and verification (MMV) requirements whilst also being cost appropriate for the CCS industry. This is a challenge which still requires work.

[8] Why CCS is Not Like Reverse Gas Engineering | Earthdoc
[9] Design of Carbon Capture and Sequestration CCS Wells | SPE/IADC Drilling Conference and Exhibition | OnePetro

Aspect	Oil and gas wells (general)	CO_2 storage wells
Corrosion Risk	Relatively low unless sour service	High due to carbonic acid; requires corrosion-resistant alloys and coatings
Cement Systems	Standard API Class G/H	Design considerations for CO_2 fluids in the injection and storage zones; may require non-Portland blends or additives
Injection Regularity	Potentially lower volume with shorter to medium time perspectives for injection wells	Long-term and high-volume injection with injectivity preservation critical
Design Life	~20–30 years	Designed for potentially 50–100+ years, including post-closure monitoring
Material Testing	Based on hydrocarbon exposure unless sour service	Must simulate CO_2 behaviour under pressure/temperature, with brine/impurity effects
Pressure	Higher for high pressure, high temperature (HPHT) or deep wells	Regular high-pressure injection with cyclic loading concerns (intermittent operation) Maximum pressure at end of well service
Temperature	Temperatures ranges from c.650°C (HPHT) to ambient in normal operations. Lower temperatures (c.0 °C) only a concern during certain operations.	Temperature ranges from ambient to -35 °C in normal operations. Very low temperatures (down to -80 °C) could be experienced during some operations.
Fluid Properties / Composition	Changes through life of field with production water often increasing rapidly.	Injection composition unlikely to change significantly but impurities play a big role in fluid behaviour. Rapid phase change is a concern.
Well Monitoring	Periodic during production	Continuous and long-term for leak detection, pressure build-up, and mechanical strain
Zonal Isolation Priority	Standard isolation for production	Critical for ensuring permanent CO_2 containment and avoiding migration

Table 6: Differences in CO_2 wells from conventional oil and gas wells

4.1 Materials and Equipment

One of the key focuses and challenges with CO_2 wells is ensuring the material compatibility for the operational lifetime of the wells, including post-operation abandonment, to ensure sustainable and continuous injection and long-lasting, leakage-free, wellbore containment. The design and construction of CO_2 storage wells must address long-term exposure to CO_2 in its supercritical or gaseous state, often under high pressure and with possible water interactions. These considerations go beyond the standard requirements of conventional oil and gas wells and include the following technical challenges:

Corrosion Resistance

- CO_2 mixed with water forms carbonic acid, which can corrode carbon steel.
- Corrosion-Resistant Alloys (CRA's) such as 13Cr, 22Cr duplex, 25Cr and austenitic stainless steels are preferred.
- Elastomers and plastics must be selected for CO_2 compatibility to avoid degradation under exposure.

Cementing Systems

- Cement degradation due to carbonic acid requires the use of CO_2-resistant cements.
- Non-Portland cement systems and additives may enhance durability.
- Cement bonding quality is critical due to the need for permanent zonal isolation over decades.

Material Testing and Selection

- Material selection must consider pressure, temperature, water content, and CO_2 purity.
- Systematic testing and qualification to ensure aligned materials selection.

Thermal and Pressure Cycling

- Injection often involves thermal fluctuations (e.g., from ship unloading or cyclic operation), risking fatigue, debonding, or microfractures in casing/cement.
- Materials must be robust against low temperatures and thermal shock.

Hydrate and Dry Ice Formation

- Blowouts or sudden depressurisation can lead to dry ice and hydrate formation, risking equipment damage and blockage.
- Materials must tolerate extreme cold and rapid phase changes.

Wellhead and Tubular Design

- Upgraded wellhead components are required to handle high-pressure, corrosive CO_2 environments.
- Long-term exposure to CO_2 demands robust packers, valves, and sealing elements.

Material and component development constitutes one of the largest focus areas and challenges within CO_2 wells. These challenges have been and are being met by the industry in the form of various component improvements and technology developments, which are discussed in the subsequent sub-sections. It should be noted that differing material needs are dependent on the position in the well and the likelihood of coming in to contact with corrosive CO_2 fluids. Potential cost savings can be found by not requiring excessive specifications for the well where that is unnecessary. The industry is considering a hybrid approach to well design and construction where materials considered qualified for CO_2 rich environments are used in zones of high risk of corrosion and standard materials are used where the risk of corrosion and is lower.

A current industry gap is understanding whether legacy operational oil and gas wells can be re-purposed as CO_2 storage wells and to what degree. There are limited number of industry case studies of oil and gas wells being re-used as CO_2 injection and storage wells. Some operators have re-used some of the outer well construction elements, such as the conductor, surface casing and some intermediate casings, such as the Porthos project[10] in the Netherlands. International and country specific standards lack guidance for method on well re-use from oil and gas to CO_2 storage and injection.

The lack of industry guidance is also proving a challenge when performing qualification and validation activities on materials and components. This is an important activity, however industry guidelines are not available for performing testing and qualification. Some general guidance can be found in industry standards, such as DNV-RP-A203, however specific component standards and guidance is lacking. The industry has put together work groups and joint industry projects aimed at establishing these guidelines and standards, which may come to exist independently or as appendices to existing oil and gas component standards. Further alignment and technical work, making sure all of the relevant guidance becomes available and establishing proper guidelines, is required by the industry. The industry also seeks to make efficiency gains in the qualification and validation of materials, component and equipment for CO_2 wells, where specific design classes / use cases may be established, for different operating cases. The rationale behind this is so that qualification tests can be harmonised and qualification activities can cover multiple project specifications, where possible, both saving time for suppliers and monetary expenditure for project developers.

Wood. has led a Joint Industry Project (JIP) to produce guidelines for setting CO_2 specifications for effective and economic CCUS chains. More information can be found in the Technology Profile box.

Industry Guidelines for Setting the CO_2 Specification in CCUS Chains (JIP)
Wood. et al.

The JIP led by Wood. in collaboration with industry and research experts (Aramco, Equinor, Fluxys, Gassco, Harbour Energy, Mitsubishi Heavy Industries, NZTC, OMV, Petronas, Shell, TotalEnergies, DNV, Heriot Watt University, IFE, NGI, NPL and TÜV SÜD), collated current knowledge surrounding impurities and produced industry guidelines for setting CO_2 specifications for effective and economic CCUS chains. The guidelines provide a holistic understanding of the impact of impurities, including in CO_2 storage, and identify the CO_2 conditioning required to meet the safety, environmental and operational requirements of CCUS projects. The two guideline reports most relevant to this roadmap are 03. Materials Corrosion and 10. Geological Storage.

Status: Completed
Website: Click here

[10] https://www.porthosco2.nl/en/project/

4.1.1 Casing and Tubing, Connections and Corrosion-Resistant Alloys

Well tubular metallurgy is a key focus area in well and completion design for CO_2 wells. The main global tubular suppliers provide tubulars for CO_2 wells, where different material grades are available. The suppliers are performing qualification testing on their tubular components (casing, tubing and connections) and cross-checking the material performance with material specialists within operators. A sample of global suppliers of alloy-based well tubulars for CO_2 wells are:

These suppliers and others have proprietary solutions for tubulars and connections for CO_2 well applications.

One challenge within the metallurgy domain is a lack of systematic testing criteria for CO_2 applications and qualification methods. Various institutions, including the American Petroleum Institute (API) and other work groups, are working to align the testing and qualification work programs for CO_2 well tubulars, similar to the API 5 series requirements for oil and gas applications.

TenarisHydril Blue® Dopeless® 3.0 premium connection
Tenaris

Tenaris state that its products, including proprietary steel grades and TenarisHydril connections, have been extensively used in CO_2 injection wells for Enhanced Oil Recovery and that its portfolio is well equipped to take on the latest challenges associated with CCUS Injection wells.

An example of one of its products is the TenarisHydril Blue® Dopeless® 3.0 premium connection made of 95Cr13S stainless steel, offering high corrosion resistance, particularly suitable for sour service and CO_2-rich environments. The Dopeless® technology eliminates the need for thread compounds, and connections are supplied RunReady™ simplifying operations.

The technology has been extensively tested under ISO 13679 CAL IV and Tenaris have conducted full-scale testing of a 3 ½" 9.2# TN 95Cr13S connection at -34°C, demonstrating that the connection maintains its gas sealability even under low temperatures. The results of this testing were presented at OMC in Ravenna and SPE CCUS Conference 2022 in Aberdeen.

Status: Commercially available
Website: Click here & Click here

VAM® 21 CLEANWELL®
Vallourec

Vallourec offers a range of seamless tubular products for CO_2 storage that help operators address material integrity challenges such as corrosion and mechanical failure.

Vallourec is active in testing and qualifying corrosion-resistant material as well as qualifying their VAM® connections' tightness. Their VAM® connection qualification protocol tests the connection's sealability in several pressure and thermal cycling phases with temperatures lowering to -80°C in blow-out scenarios. The 3 ½" VAM® 21 CLEANWELL® was the company's first connection tested according to such a rigorous CO_2 injection protocol.

VAM® connections demonstrate reliable sealability and mechanical resilience, even under high tension, compression, and temperature changes. Additionally, Vallourec's CLEANWELL® dope-free coating for VAM® connections can further enhance the environmental sustainability and anti-corrosion properties of the connections.

Status: Commercially available
Website: Click here & Click here

Casing and Tubing for CO_2 wells
Nippon Steel

Nippon Steel offers a comprehensive range of casing and tubing solutions tailored for CO_2-rich environments including martensitic stainless steels (e.g. 13Cr and Super13Cr), duplex stainless steels, and nickel-based alloys; to be selected based on CO_2 concentration, H_2S content, chloride levels, and temperature. These materials are engineered to resist corrosion, stress cracking, and collapse under extreme well conditions, including sour service and high-pressure injection scenarios.

The New SM-Series grades are particularly suited for wet CO_2 corrosion service. Their trusted manufacturing processes coupled with premium connection designs (including VAM® 21 by Vallourec) ensure long-term integrity and reliability in CO_2 injection wells. Material selection is guided by their detailed chart that considers the full lifecycle of the well, helping operators optimise performance and safety in CCS deployments.

Status: Commercially available
Website: Click here & Click here

Casing and Tubing for CO_2 wells

Corrosion Resistant Alloys (CRA)

CRA provides high-quality speciality alloy piping and tubing. CRA's alloy solutions for CCS Wells include: Martensitic Stainless Steels, Duplex Stainless Steels, Highly Alloyed Austenitic Stainless Steels, and Nickel-base Alloys. CRA has an experienced metallurgical team to evaluate unique conditions of CCS projects and guide material selection. CRA also partner with third party testing and engineering companies globally equipped to test the unique conditions of clients CCS wells.

CRA operate a unique Just-In-Time model offering reduced lead times for premium OCTG and tubulars. They keep reserved capacity to accommodate urgent needs for corrosion-resistant alloy pipe in standard and non-standard specifications, lengths and quantities. Their current size capability ranges from 2-1/16" to 10-3/4" OD with wall thicknesses up to 1.925" but is expected to expand to 13 3/8" OD.

Status: Commercially available

Website: Click here & Click here

There is a Joint Industry Project being facilitated by DNV, "Materials performance in CCS Wells JIP" focusing on the damage mechanisms of tubular performance in CO_2 wells. The project aims at characterising the failure (damage) mechanisms for corrosion-resistant alloys used in CO_2 injection and storage wells. The project started in December 2023 and has several industry partners. Further information on the JIP is provided in the Technology Profile box.

Materials performance in CCS Wells Joint Industry Project (JIP)

DNV, ExxonMobil, CNPC, Shell, OneSubsea, Vallourec, JFE Steel Corporation, TFMC

The JIP led by DNV, in collaboration with ExxonMobil, CNPC, Shell, OneSubsea, Vallourec, JFE Steel Corporation, and TFMC, aims to address the damage modes associated with downhole and wellhead materials for CCS applications. The goal of the JIP consortium is to comprehensively understand and characterise the damage mechanisms that corrosion-resistant alloys (CRAs) face in CCS well applications, which include both depleted gas fields and new fields. By doing so, they aim to facilitate materials selection, define operational windows, and ensure the long-term performance of materials in CCS storage wells. The primary objective of the JIP is to develop guidelines for the use of CRAs in CCS well applications through:

1. Identifying the role of key environmental factors on damage modes in CRAs based on preliminary thermodynamic calculations.
2. Characterising the performance of CRAs and establishing environmental limits for localised corrosion and SCC in CCS storage wells.
3. Creating a framework to translate qualification test observations into long-term performance predictions in service.

Status: Under development

Website: Click here

Additionally, research performed by Shell and OCAS (OnderzoeksCentrum voor de Aanwending van Staal)[11] demonstrates the applicability and suitability of premium OCTG (Oil Company Tubular Goods) tubing connections for CCS wells. The Shell and OCAS research covered a critical topic of the threaded tubular connections, where they have been and are considered to be a potentially critical failure mode of the CO_2 wells' construction. In this work, the strength and sealing of oil field casing and tubing (OCTG) connections has been evaluated for CCS application. A full-size connection test has been executed as well as three small-scale tests under downhole CCS conditions. The study indicated that it is proposed that OCTG connections can be used for CCS applications, provided the materials used are suited for CCS service.

One available tool for assessing and evaluating tubular availability is the Global Warehouse – PipeSearch[12], an online portal for browsing tubular availability based on grade, size, location and other specifications. PipeSearch is a CRA affiliate.

Operators have shown interest in exploring the use of alternative material technologies for downhole tubulars with technologies using alternative materials emerging for CO_2 wells. These include:

- MaxTube - Duoline® 20 fibreglass-lined tubing
- CRA Tubulars - Titanium-lined composite tubulars (TCT)
- Vallourec - Glass Reinforced Epoxy (GRE) liners
- Composite Lining Systems - GlassBore®
- Composite Lining Systems - GlassWrap®
- NOV - Tuboscope™ TK™-Liner

More information is available on each of these within the Technology Profile boxes.

Duoline® 20 - fibreglass lined tubing

MaxTube

Duoline® 20 by MaxTube is a glass-reinforced epoxy (GRE)-lined tubing system designed to mitigate downhole corrosion in oil, gas, and CCS wells. The liner is manufactured using a filament winding and high temperature cure process, then inserted into carbon steel tubing to combine the mechanical strength of steel with the corrosion resistance of fiberglass.

With over 110 million feet installed in over 55,000 wells worldwide, including over 30 million feet in CO_2 injection wells, Duoline® 20 has a track record in environments containing CO_2, H_2S, and other corrosive fluids including water-alternating-gas (WAG) fields, sour gas services, and chemical disposal wells. It operates reliably up to 121°C, maintains full pressure integrity, its smooth internal bore improves flow efficiency, and the system is compatible with both API and premium connections. Additionally, Maxtube's Portable Lining Units (PLUs) allow on-site installation, reducing logistics costs and enabling use of existing pipe stock.

Status: Commercially available

Website: Click here & Click here & Click here

[11] https://www.sciencedirect.com/science/article/abs/pii/S175058362300004X
[12] https://pipesearch.com/global-warehouse/

Titanium-Lined Composite Tubulars (TCT)

CRA Tubulars

TCT by CRA Tubulars combine titanium's robustness, carbon fibre's agility, and aerospace epoxy's resilience to craft technically superior and economically viable downhole completion tubing and connections. Shell GameChanger is funding CRA Tubulars to advance their cutting-edge Titanium Composite Tubular technology.

CRA Tubulars aim to offer rapid delivery times (~2 months) compared to traditional alloy alternatives, and lifecycle cost savings due to superior longevity in corrosive environments, expected to exceed 20-30 years of service life.

Status: Under development
Website: Click here

Glass Reinforced Epoxy (GRE) liners

Vallourec

GRE liners by Vallourec are installed inside carbon steel tubing to shield against CO_2, H_2S, O_2, high salinity, and microbial activity. GRE liners are compatible with Vallourec's premium VAM® TOP and VAM® 21 connections without requiring design modifications, and have been tested to ISO 13679: 2002 CAL IV standards up to 120°C.

The GRE liners can be used in wet CO_2 injection, water injection, and production wells, and are a good alternative to costly CRA grades and have been successfully deployed in regions like the North Sea, Middle East, and offshore Brazil, including a major contract with Petrobras for offshore oil and gas wells.

Status: Commercially available
Website: Click here

GlassBore®

Composite Lining Systems (CLS)

GlassBore® by CLS is a GRE lining service designed to protect the internal diameter of casing and tubing from corrosion in harsh downhole environments. CLS installs GlassBore® GRE liners into new or used tubing and casing. Fabricated from fiberglass-reinforced epoxy resin, GlassBore® provides a durable, impact-resistant barrier that eliminates exposure to corrosive fluids and gases.

GlassBore® GRE has a long history of documented performance with a history in US Shale Operations. There customers in secondary and tertiary production (CO2 and corrosive water injection) form the second largest US market for GRE-lined tubular products. They have years of experience protecting tubing installed into CO_2 and water injection wells, corrosive production wells and acid gas injection wells.

Status: Commercially available
Website: Click here

GlassWrap®

Composite Lining Systems (CLS)

GlassWrap® by CLS is an epoxy-wetted fabric wrap applied externally to tubular products to protect against outer diameter (OD) corrosion in corrosive well environments. Since 2013, over three million feet of GlassWrap® have been installed on tubing and casing placed in corrosive service. GlassWrap® may be applied to tubing installed in an unprotected annular space (between packers, for example).

Status: Commercially available
Website: Click here

Tuboscope™ TK™-Liner

NOV

TK™-Liner by NOV is a GRE lining system developed by Tuboscope™ to protect both new and used downhole tubulars and flowlines from corrosion in harsh environments. It offers a high-performance barrier against corrosive fluids and gases, while also providing thermal insulation, making it suitable for injection, disposal, production, geothermal and CCUS applications. TK™-Liner systems are available in various configurations, including TK-Fiberline, TK-Fibreline II, TK-Ring, and TK-Ring II, each tailored to different pipe types and connection styles, with most requiring no thread modifications

Status: Commercially available
Website: Click here

As highlighted in this section, appropriate materials for CCS wells, concerning casing and tubing, connections and CRA, are widely available and therefore new materials do not need to be developed. However, new protocols for the qualification and validation for these materials are required for use in CCS. Some companies are starting to establish a standardised set of grades which could be used for CCS wells. A key challenge for operators is still the costs associated with these premium materials so understanding exactly where and where not in the well higher-grade materials are required will help ensure they are not exceeding specification requirements and subsequently keep costs down. Additional data coming out of new CCS developments will assist with this and will also assist material providers in optimising their inventories.

4.1.2 Valves

For CO_2 wells the operation and reliability of valves in the well as well barriers, have been considered an industry challenge and an important development area. The challenges for downhole safety valve operation includes thermal effects and potential start/stop behaviour in CO_2 injection and storage wells, in addition to the CO_2 well fluids interacting with the valve materials. The focused efforts include an executed JIP facilitated by the NZTC, where multiple operators, together with suppliers, aimed at qualifying downhole safety valves to the environmental conditions relevant for CO_2 injection, monitoring and storage wells. The JIP has brought the industry forward by readying the downhole safety valve components for use in CO_2 wells, by demonstrating their functionality in the expected environmental conditions of operational CO_2 wells. More information on the JIP is included within the "Subsurface Safety Valve (SSSV) for CCS" Technology Profile box. Technology profiles have been included for the tubing retrievable safety valve offerings from the three tier 1 supply chain companies who were part of the JIP, and also for Weatherford.

Subsurface Safety Valve (SSSV) for CCS

NZTC in collaboration with nine industry partners and three technology developers

Status: Completed
Website: Click here

The NZTC led a JIP which included nine industry partners (bp, Chevron, EBN, Eni, Equinor, Harbour Energy, TotalEnergies, Shell, and Storegga) and three tier 1 supply chain companies (Halliburton, SLB, Baker Hughes) to test and qualify a range of subsurface safety valves (SSSVs) for use in CO2 wells. The JIP focus on tubing retrievable subsurface safety valves.

CO_2-rich environments present unique challenges such as extreme low temperatures caused by the Joule-Thomson (JT) cooling effect which can drop temperatures to –78°C during rapid depressurisation. Traditional SSSVs are not rated for the extreme low temperatures with most commercial valves only certified to –5°C, leaving a significant gap in CCS readiness. Additionally, the industry lacked established standards or testing protocols for using SSSVs in CCS applications. To close this gap, the JIP developed a bespoke SSSV qualification programme based on API 14A G.3 standards adjusted for CCS conditions, validating valve performance across 500 operational cycles using nitrogen and operated in temperatures from 85°C to –35°C. The valves were successfully tested down to –78.5°C and also included modified API 14A 12th edition G.4 tests at –35°C. The project saw each supply chain company test two valves each in two different sizes from 3 1/2" to 5 1/2". The outcome is a portfolio of commercially available, CCS-qualified SSSVs, and a proposed update (new test procedure) to API 14A marking a step toward establishing a CCS industry standard.

Thunder™ Tubing-Retrievable Subsurface Safety Valve (TRSSV)

Baker Hughes

Status: Commercially available
Website: Click here

The Thunder™ TRSSV combines proven features from the Titan™ and T-Series™ valves to deliver strong performance in both shallow and deep settings (304.8 to 2,834.6 m), to withstand temperatures up to 149°C and pressures between 5,000 and 10,000 psi. The valve features metal-to-metal thread for high tensile strength and sealing, and a non-elastomeric dynamic seal assembly that eliminates decompression risk and thermal degradation.

It is innovative in its through-the-flapper self-equalising system, ensuring a high-integrity seal without conventional failure modes. It also has a puncture communication system that maintains an uninterrupted fluid path to the piston, reducing the risk of accidental activation. Available in two models, standard (2 3/8" to 7") and Thunder-T (2 3/8" to 5.5"), for slimline or larger valve diameters. The 3 1/2" and 5 1/2" valves were tested in the NZTC CCS SSSV JIP.

TRMAXX™ 5E & SlimTech™ Valve - Surface-Controlled subsurface safety valve

SLB

Status: Commercially available
Website: Click here
& Click here
& Click here

The TRMAXX™ and SlimTech™ SCSSV are hydraulically actuated safety valves designed for both O&G and CCS applications. They feature a rod-piston actuator with non-elastomeric dynamic seals and a metal-to-metal INCONEL® 718 flapper closure to ensure pressure integrity & reliability. They have working pressure of 5,000 psi, an operating temperature of -35 to 80°C with survival temperature down to -78.5°C, and a setting depth up to 1,829 m.

These valves have been rigorously tested and qualified per the requirements of API Spec 14A with their performance exceeding the certification requirements. The 3 ½", 4 ½" and 5 ½" TRMAXX™, and 7" SlimTech™ Valves are qualified as part of SLB's Sequestri carbon storage solutions family with the 4 ½"and 5 ½" valves having been tested in the NZTC CCS SSSV JIP.

NeoStar™ CS tubing retrievable safety valve (TRSV)

Halliburton

The NeoStar™ CS TRSV is based on the field proven SP™ safety valve design, featuring a single rod-piston, non-elastomer flapper mechanism and metal-to-metal sealing within the control system to help minimise leak paths and ensure gas-tight integrity. It earned the "CS" designation by qualifying it to rigorous industry test protocols, demonstrating operability and survivability at temperatures as low as -35°C and -78.5°C respectively.

It is available in four sizes, 3 ½", 4 ½", 5 ½" and 7", with pressure rating of 10,000 PSI with the exception of the 7" tool which is pressure rated to 7,500 PSI. API 14A validated. To support permanent CCS monitoring operations, slim OD solutions are available that allow the passage of gauge, fibre-optic and hydraulic lines. The 3 ½" and 4 ½" valves were tested as part of the NZTC CCS SSSV JIP.

Status: Commercially available
Website: Click here

Optimax™ Series Safety Valves

Weatherford

Optimax™ Series Safety Valves are designed to deliver high-integrity well control featuring metal-to-metal sealing, non-elastomeric flapper designs, and hydraulic actuation systems that ensure reliable seal performance under high pressure conditions. They are available in tubing-retrievable and wireline-retrievable configurations ranging in size to accommodate 2 3/8" to 7" tubing, they are rated for pressures up to 15,000 psi and for temperatures up to 177°C.

The valves have been certified to API 14A and API Q1 specifications and are slam tested at rates above industry standards. Further, each family of safety valves undergoes Weatherford's rigorous test programme to verify durability and reliability. The Optimax™ valve passed C3 validation emulating subzero temperature in CO_2 injection environment; and is undergoing full life cycle testing to further validate long term durability.

Status: Commercially available
Website: Click here

Demonstrating the appetite for industry to collaborate on the development and qualification of materials and equipment after the success of the SSSV JIP, two new JIPs are set to launch in the near future. The first on shear seals, which is discussed further in the section 4.1.3, and the second on wireline retrievable safety valves (WRSVs). The WRSV JIP is looking to test the bespoke qualification programme, developed for the SSSV JIP, on a selection of WRSVs. There are multiple companies with WRSVs which may be part of the new JIP including Intewell, Oilenco, Halliburton, Wellvene, Tejas Research and Engineering, Weatherford, Baker Hughes and SLB.

Christmas tree valves used in CO_2 wells are similar to oil and gas applications, with ongoing testing and qualification, aiming at demonstrating the functionality and reliability for CO_2 injection conditions. Further details on the wellhead and christmas tree technologies for CO_2 wells are discussed in section 4.1.4.

4.1.3 Seals and Packers

Similar to the valves in CO_2 wells, the seals and packers are also vital well barrier elements, needing validation and qualification, prior to implementation. The production packer is an important well construction element, functioning as a primary well barrier element, providing an isolation between the lower completion (tubing and other equipment) and the production casing. Seals are included in the production packer and other well equipment, for example completion components. Suppliers, together with operators are performing testing and qualification for extended ranges of application, both in terms of temperature and fluid composition/compatibility for CO_2 wells applications. Other concerns, such as fluid properties and behaviour, may impact the seals and packers, as well as the potential cyclical nature of the CO_2 injection. While focus has been on qualifying existing oil and gas seals, both downhole and on drilling equipment, other sealing solutions / materials are beginning to present themselves for development, qualification and commercialisation. These other seal alternatives are typically different sealing materials.

A couple of examples of packers and seals include:

Aptum™ seals and Premier™ NXT Packers

Baker Hughes

Baker Hughes recognises that completion integrity is key for maintaining storage integrity over the life of a CCS project. Carbon storage applications can create corrosive environments when CO_2 becomes mixed with water and other fluids in the wellbore and consequently completion equipment can be exposed to these corrosive fluids. To counteract the effect of the corrosive fluids, corrosion inhibitors are used which protect the metallic elements such as tubing, packer body etc. however corrosion inhibitors can degrade elastomers used in seals. In the case of elastomers which can withstand corrosion inhibitors they tend to have temperature limitations. To address this challenge, Baker Hughes developed the Aptum™ seal. As stated in "State-of-the-Art-CCS-Technologies-2025-Global-CCS-Institute.pdf", "Aptum™ seal systems, along with industry-leading packers such as the Premier™ NXT removable production packer, perform at lower, more appropriate temperatures for CCS and yet maintain excellent chemical compatibility and mechanical properties. With Aptum™ seals in the completion, operators can better protect their metal tubulars and equipment without fear of elastomer degradation."

Status: Commercially available
Website: Click here

Welltec® Annular barrier (WAB®)
Welltec

Welltec provide a CO_2 resistant Welltec® Annular Barrier (WAB®) technology which secures the well against annulus CO_2 leakage. Welltec packers are tested in compliance with ISO 14310 V0: the highest level of gas-tight testing criteria. Isolation is ensured by expanding the packers between the base pipe and the casing or the borehole via the controlled application of pressure. The versatile WAB solution conforms to the exact wellbore geometry to provide life-of-well isolation, integrating seamlessly with additional elements of the CCS system.

Status: Commercially available
Website: Click here

Welltec are working to develop a broader range of products specifically for CCS applications and has a full-scale Test Flow Loop centre in Denmark which is designed and constructed to allow CCS operators to test full-scale down hole well components within a high-concentrate CO_2 environment, at high pressures and temperatures, and with a mixture of chosen impurities.

As mentioned in the previous section, the NZTC is in the process of developing a new JIP involving industry partners and technology developers with the aim of qualifying the shear-seal device for CCS wells. Ensuring these devices work in an emergency situation, potentially under extreme cold conditions as a result of the Joule-Thomson effect, is of paramount importance for well control in CCS wells. More is discussed on well control in section 4.2.

There are numerous vendors supplying shear-seal devices for the oil and gas industry such as Unity, Kinetic Pressure Control, Hunting, NOV, Innovex (DrillQuip), SLB and TechnipFMC but confidence needs to be built in their ability to work effectively in CCS wells.

Shear-Seals JIP
NZTC (in collaboration with industry partners and technology developers – tbc)

The Shear-Seal JIP will aim to qualify the shear-seal device for low temperatures typically seen during carbon injection into a well but also during the intervention of a carbon storage well. The JIP is anticipated to kick off in January 2026 and will complete testing throughout 2026.

Status: Awaiting Kick-off
Website: Click here

4.1.4 Wellheads and Christmas Trees

Wellhead and christmas tree equipment designed and implemented for CO_2 wells is intrinsically similar to oil and gas wellhead and christmas tree equipment, both for onshore wells and offshore platform and subsea wells. The specific material challenges and flow assurance challenges highlighted in the introduction to section 4.1 are relevant for the wellhead and christmas tree equipment. Two additional specific challenges for wellhead and christmas tree equipment include, firstly the operational functionality for periodic well integrity testing, such that integrity of the well barrier elements can be tested and secondly, potential longer equipment and component lifetime requirements.

Operators and suppliers express interest in standardising the technical specifications of wellheads and christmas tree equipment into different application ranges, as well as standardising the qualification methodology and baseline standards. It is expected that this industry development is continued in industry work groups and updates to international standards, such as API 6A for wellhead equipment

Many of the traditional oil and gas suppliers deliver wellhead and christmas tree equipment, where, for example, Aker Solutions (One Subsea) supplied the wellhead and christmas tree equipment for the Northern Lights project in Norway. Other vendors are applying, qualifying and validating the wellhead and christmas tree equipment for CO_2 wells use cases.

CCS Wellhead Solutions
Baker Hughes

Baker Hughes offers a range of wellhead solutions for CCS wells including innovative compact solutions, such as the MS-TTL wellhead system, and conventional wellhead solutions. The company's solutions tackle extreme temperatures and harsh well conditions and are built upon decades of oil and gas experience, with a track record in CCS since 1996. Temperature conditions have been rated to API-Temp Class K of -60degC in case of uncontrolled CO_2 release and they have operating pressures up to 10,000 psi or greater if required.

The Global CCS Institute report (pg.216) provides an informative summary of Baker Hughes' solutions.

Status: Commercially available
Website: Click here

CCS Christmas Tree Solutions

SLB - OneSubsea

SLB OneSubsea, a joint venture between SLB, Aker Solutions and Subsea7, delivers a range of subsea solutions that span both carbon management and production infrastructure. It's subsea christmas trees can operate in temperatures ranging from -18°C to 176°C and pressures up to 15,000 psi. Their christmas tree products include the CO_2-control-valve xmas tree (CO_2 XT) suitable for injector wells. Supplied to the Northern Lights project they control the injection of liquified CO_2 into the saline aquifer. In June 2025 it was announced that SLB OneSubsea had been awarded the contract to deliver two new satellite subsea CO_2 injection systems with associated tie-in equipment for the Northern Lights phase two project increasing the capacity to a minimum of 5 million tonnes of CO_2 per year.

Status: Commercially available

Website: Click here

4.1.5 Cement and Alternative Barriers

Cement barriers in CCS wells face unique challenges due to the potentially corrosive downhole conditions, injection cycles, and long-term storage requirements. Conventional Portland cement could degrade in the presence of carbonic acid and combined with damage from downhole stresses, long-term well integrity could be compromised making the selection of the right materials imperative to promote long-term well integrity.

Cement is a key barrier component in CCS wells, which must retain its integrity throughout the entire lifetime of the well. A typical failure mode is formation of microannuli, i.e., cement debonding from the steel casing or surrounding rock (Ravi et al., 2002[13]; Bois et al., 2011[14]). Such microannuli may form due to the repeated changes in temperature and pressure which occur within the wellbore with cyclic injection, causing the casing and cement to contract and expand. Over time the cement may develop cracks and fractures or de-bond thus losing the ability to properly seal and lead to potential CO_2 migration.

The carbonation reaction which Portland cement undergoes in CO_2 environments can also chemically alter and degrade cement. Portland cement contains components which react with carbonic acid which is formed when CO_2 comes in contact with water. This reaction can lead to brittleness in the cement making it more vulnerable to fracture and crack thus increasing its permeability and the chance for CO_2 migration.

Proper placement and setting of cement and well construction practices can deliver barriers which can withstand long-term cyclic injection and safe storage requirements. However, with the risks associated with traditional Portland cement, use of materials that can withstand dynamic stress changes and are more resistant to the impact of carbonation are recommended to improve long-term well integrity.

This has led to the development of CO_2-resistant cements. CO_2-resistant cements are specially engineered wellbore cements designed to withstand the harsh conditions encountered in CO_2 injection wells. Unlike conventional Portland cement, CO_2-resistant cement incorporates additives and modified chemistries that enhance its durability. These formulations reduce permeability, improve mechanical strength, and resist carbonation, thereby maintaining long-term well integrity.

It should be noted however that it may not be necessary to utilise corrosion resistant cements in the full length of the wellbore. Ceyhan et al. 2022.[9] recommended that CO_2 resistant cement is used from TD to at least 500ft shallower than the caprock but that above this depth, normal oil and gas cements could be used. This potentially could provide cost savings.

[13] Ravi, K., Bosma, M., Gastebled, O. 2002. Improve the Economics of Oil and Gas Wells by Reducing the Risk of Cement Failure. Paper IADC/SPE 74497-MS presented at the IADC/SPE Drilling Conference held in Dallas, Texas, 26–28 February

[14] Bois, A.-P., Garnier, A., Rodot, F., Sain-Marc, J., Aimard, N. 2011. How to Prevent Loss of Zonal Isolation Through a Comprehensive Analysis of Micro-Annulus Formation. SPE Drilling&Compl. 26 (01)124719-PA

CorrosaCem™ & CorrosaLock™
Halliburton

Halliburton's CO_2 resistant cement systems, CorrosaCem™ and CorrosaLock™, are designed to provide durable zonal barriers for CCS wells by significantly improving chemical resistance to CO_2 induced corrosion, minimizing permeability, and enhancing ductility for cyclic injection integrity. These systems use reduced-Portland blends with proprietary additives and can use supplementary cementitious materials (SCM) that remove or minimize components susceptible to attack by carbonic acid while reducing the permeability of the system.

CorrosaCem™ cement system employs non-reactive supplementary cementitious materials (SCMs) and additives which can include fibers and elastomers and other proprietary additives to create a crack-resistant, low-permeability matrix, demonstrated to withstand repeated pressure cycles and chemical exposure.

CorrosaLock™ cement system combines Portland cement with WellLock® resin, forming an adhesive layer and internal spheres that shield cement grains and dramatically reduce porosity, resulting in superior corrosion resistance, enhanced elasticity, and shear bond strength, reducing debonding with improved anchoring to casing and formation, minimizing the risk of gas migration.

Halliburton's CO_2-resistant cements have a track record with successful CCS related deployments in North America, Japan, and the Gulf of Mexico with cement bong logs confirming coverage in each project.

Status: Commercially available
Website: Click here
Click here

EverCRETE™
SLB

SLB's EverCRETE™, part of the Sequestri carbon storage solutions family, is a specialised CO_2-resistant cement system engineered to deliver long-term zonal isolation and integrity in CCS wells and other high-CO_2 environments. It is specially designed to resist corrosion from wet supercritical CO_2 and CO_2-saturated water through a proprietary blend of materials that minimises the use of Portland cement. Critical to well integrity in CCS, EverCRETE also supports integration with self-healing additives that can autonomously repair microcracks and annuli upon contact with migrating CO_2, restoring zonal isolation.

The system has had successful CCS application in an onshore CCS project in Hungary to eliminate sustained casing pressure, and two offshore projects in Norway and Australia.

Status: Commercially available
Website: Click here

PermaSet cement system
Baker Hughes

The PermaSet™ cement system, including PermaSet R™ and PermaSet Ultra™, is a CO_2 and H_2S resistant cement system. The reduction or absence, in the case of PermaSet Ultra™, of Portlandite ($Ca(OH)_2$) in the cured matrix, eliminates weak points and greatly reduces carbonation and chemical attack from CO_2 and other aggressive agents. PermaSet incorporates specialised additives and optional resin/polymer (PermaSet R™ and PermaSet Ultra™ respectively) enhancements to lower permeability, improve mechanical properties, and boost resistance to CO_2.

PermaSet's low heat evolution during setting mitigates cracking and shrinkage, further supporting well integrity

Status: Commercially available
Website: Click here

In addition to alternative CO_2-resistant cements, several other technologies, emerging in the plugging and abandonment of oil and gas wells, have also been identified for potential use in CCS wells. These include and are not limited to:

- Polymer-based barrier technologies, such as those provided by Resolute Energy Solutions, where pumpable mixtures can solidify and function as permanent, long-lasting well barrier elements. The polymer-based barriers can be pumped down from the surface, rapidly expand to seal zones, and remain impermeable to both fluids and gases. They strengthen existing barriers, enable rigless plug-and-abandonment operations, and eliminate the need for expensive drilling remediations.
- Resins and epoxy, such as those provided by CannSeal / Interwell, WellCem, DVG (Disruptive Value Group AS), ExperWell AS, ResAMBER and Western Petroleum Management (WPM), are potential solutions that use specialised resin or epoxy chemistries aimed at improving pressure resistance, adhesion, and long-term durability compared to traditional cement-based plugs.
- Biomineralisation, such as provided by BioSqueeze, which use low-viscosity fluids infused with naturally occurring soil bacteria, which, when injected into the well, triggers the in-situ formation of calcium carbonate. This newly formed rock grows within microfractures and narrow leakage channels.
- Bismuth based alloys, pioneered by BiSN, Interwell, Wellstrøm, Isol8, Indium, where bismuth-based alloys serve as permanent plugging materials for wells using unique metallurgical properties. When melted, these alloys exhibit a low viscosity similar to water and high density, which allows them to flow into micro-annuli, cracks, perforations, and other hard-to-reach spaces within the wellbore before hardening more effectively than cement.

4.1.6 Mitigation Tools and Methods

In order to ensure optimal performance of the materials and equipment in CO_2 wells over their lifetime, two key technologies have been identified, firstly handling tools of downhole tubulars and completion components and secondly corrosion inhibitors to prevent corrosion in CO_2 wells.

As mentioned in section 4.1.1, CRA tubulars will often be used in CCS wells to deal with the corrosive environment normally present and help ensure well integrity. These tubulars must be handled and installed carefully as any damage incurred, such as impressions or cuts, during the installation process can end up being sites of accelerated corrosion. Specific equipment for handling dedicated tubulars and equipment for CO_2 wells has been developed in order to eliminate and reduce damage to critical components. One example is Expro's Frank's Tubular Running Service (TRS) which offers a true CRA system including the patented Collar Load Support System (CLS™) and the FLUID GRIP® technology. More information can be found in the technology profile box and also within the [Global CCS Institute 2025 report (pg. 232)](#).

In addition to the tubulars run as part of the well construction and completion, other critical well barrier and well productivity equipment on the completion string may need special focus, such as downhole safety valves, downhole gauges and instrumentation technology and permanent packers. Some companies, such as dti, are starting to look at this. [dti highlight that CCS wells completed with composite or GRE lined tubing require specialist intervention tools](#). They have experience plugging, perforating and intervening in fibre and fibre lined tubing and offer an extensive range of slickline products suitable for the application.

Collar Load Support (CLS)™ System and Fluid Grip Tong®
Expro

When paired together, the CLS™ system and FLUID GRIP Tong® forms a handling system designed to eliminate marking and mechanical damage during the running and retrieval of completion tubulars including corrosion resistant alloys. The CLS™ system supports tubulars via the load face, avoiding stress concentrations that can lead to corrosion cracking. It features a shock table that gently decelerates joints during load transfer and preserves coupling integrity, supports both surface mount and flush mount configurations, and is compatible with control lines and large umbilicals. The FLUID GRIP Tong® conforms to the shape of the tubular reducing stress, distortion and galling and eliminating die penetration marks to mitigate corrosion concerns and prolong well stability.

Status: Commercially available
Website: [Click here](#)

As an added line of protection, corrosion inhibitors can be applied to protect wellbore materials and equipment such as tubing, casing, and surface equipment. Corrosion inhibitors are chemical compounds specifically formulated to prevent the aggressive effects of carbonic acid (H_2CO_3), which is highly corrosive to steel and other common metallic materials. Over time, this can lead to pitting, uniform corrosion, or even catastrophic failure of the well's metal components. Corrosion inhibitors work by adsorbing onto the metal surfaces, forming a thin, protective film that limits direct contact with corrosive species, thereby reducing both the rate and severity of corrosion. There are two main types of corrosion inhibitors used in CO_2 wells: anodic inhibitors, which slow down the metal dissolution reaction, and cathodic inhibitors, which reduce the reduction reactions (like hydrogen evolution) on the metal surface. Both types of corrosion inhibitors have been used extensively in the oil and gas industry. The corrosion inhibitors can be continuously injected or applied in batch treatments, and they are often combined with other additives, such as oxygen scavengers and scale inhibitors, to provide comprehensive protection under high-pressure, cold-temperature and multiphase conditions found in CO_2 storage wells. While corrosion inhibitors aim to prevent the onset of corrosion on the wellbore elements, applying the inhibitors deep into the well, for example in the A-annulus below the production packer and in the lower completion section of the tubing, could be difficult to perform successfully and may interrupt CO_2 injection operations. Consequently, the need for corrosion resistant alloys (materials) in well tubulars may also be required, in addition to corrosion inhibitors.

Case Study

The Northern Lights CO_2 storage project

The Northern Lights CO_2 storage project is a high-profile example of large scale offshore CO_2 storage. With the start of CO_2 injection at Northern Lights in Q3 2025, the viability of this project is demonstrated, with long term integrity and injectivity to be proven over the projects life span. Northern Lights has received significant state support by the Norwegian government and the studies, approaches, designs and operations are meant to be made public as possible. In this regard, the Northern Lights project has presented several papers and industry presentations describing the well design for the CO_2 injectors. Several key notes and takeaways, as presented[15] by the Northern Lights project, include:

- The CO_2 injector wells are designed for a life of 25 years
- Well barriers are established and designed according to Oil and Gas governing rules
- Mixing of liquid CO_2 with saline formation water introduces a corrosion risk and 25% chrome will be used in the lower completion and bottom part of the upper completion and the bottom part of the liner.
- CO_2 resistant cement with suitable properties for the production liners
- Chemical clean up with breaker
- Compatibility tests on elastomers were performed
- Equipment qualification at expected pressure/temperature
- A monitoring program to detect CO_2 leakage (check CO_2 plume migration over the time)
- DHPTG to monitor injection pressure but also pressure in the A-annulus
  - Option DTS/DAS in phase 2 wells
- Annulus pressure management refers to an engineering approach ensuring that casing annulus pressures do not challenge the well's integrity during the life of the well
  - Primary and secondary barriers will be monitored by the top-up/bleed-off method
- Blow out and kill studies have been performed
- Designed for the possibility of intervention with coiled tubing, wireline and slickline

[15] Presented by Northern Lights project at SPE Workship: Well Integrity in a Changing World, Sept 2022

4.2 Intervention and Workover

During the lifetime of a storage project, wells within the storage complex (both new and legacy), may need to have interventions, be worked over and potentially re-drilled or re-completed to maintain operational efficiency and provide long-term integrity assurance. The drivers for this work include integrity evaluations to understand the well or near wellbore related leakage risks, wellbore and reservoir logging and stimulation, repair of downhole components and mitigation of known or suspected well-related leakages. While routine in oil and gas operations, the presence of CO_2 or CO_2-enriched fluids in the well when performing intervention and workover operations could pose significant challenges. The presence of CO_2 or CO_2-rich fluids in the wellbore offer similar challenges as described in section 4.1, where lower temperature and thermal effects, CO_2 and other wellbore corrosivity, potential plugging, and flow related challenges are also impactful for CO_2 well operations. This section will cover:

- Well control and CO_2 handling in drilling and intervention systems
- CO_2 wells intervention equipment
- Intervention integrity evaluations

Many of the systems and much of the equipment used in CO_2 well intervention and workover are similar to oil and gas applications, however challenges exist in ensuring technology validity when directly applying traditional oil and gas technologies for CO_2 well workover and intervention. When applying oil and gas intervention and workover equipment, it is important to ensure the use case and limitations are valid. When these limitations are not valid or exceeded, additional technology qualification may be required to demonstrate the robustness of the technologies toward individual operational and safety threats such as corrosion, well integrity, monitoring functionality or specialised requirements.

In addition to the applicability and validation of the hardware, procedures and risk management of the safety and operational risks are important to consider when intervention and workover operations on CO_2 wells take place. There are different well conditions relative to oil and gas intervention and workover conditions, and well control and flow assurance challenges may present themselves.

It should be recognised that, outside of EOR well intervention and workover, there is a general limited operational history for well workover, intervention and re-drilling and re-completion for CCS wells. As more case studies and industry experience is gathered, knowledge sharing is encouraged to ensure safety and operational efficiencies in workover and intervention activities on CCS wells.

Pre-Intervention Planning	Execution Preparation	Intervention Operations	Post-Intervention Evaluation
Define objectives, colelct and analyse historical well data, assess reservoir conditions, perform a site-specific risk and contingency analysis focused on CO_2 phase behaviour, corrosion, and integrity threats, and select appropriate intervention methods and equipment.	Mobilise personnel and equipment capable of safe operation in CO_2 environments, establish site safety, implement well control measures such as deploying blowout preventers, and set up surface systems for the planned intervention.	Condust the chosen intervention, which may involve slickline, wireline, coiled tubing, pumping fluids, chemical treatments, or mechanical repairs, while monitoring well pressure and integrity in real time.	Retrieve tools, restore well status, analyse results and performance data, document the intervention, and update maintenance or monitoring schedules as needed.
Majority of required technologies already existing - transferred from oil and gas industry. Emerging modelling and simulation software adapted specifically for CO_2 wells and the unique challenges presented.	Emerging technology within the well control space for CCS wells such as Noble's Modular CO_2 Handling Package.	Majority of required technologies already existing - transferred and adapted from oil and gas industry. Case studies of successful deployments of intervention tools on CCS wells emerging.	

Figure 3. Typical intervention workflow and technology developments

4.2.1 Well Control and CO_2 Handling

Handling CO_2 in the drilling fluid well stream is a challenge as it presents additional well control considerations. Aspects to consider for CO_2 well control relative to conventional oil and gas drilling include:

- Phase behaviour and rapid expansion
  - CO_2 Phase Transitions: CO_2 can exist as a gas, liquid, or supercritical fluid depending on pressure and temperature. In well control events (kicks or blowouts), pressure drops rapidly, causing:
    - Flashing from liquid/supercritical to gas, which increases volume dramatically (up to ~500x expansion).
    - Gas influx acceleration compared to hydrocarbons, making choke and kill operations more difficult.
    - Joule-Thomson Effect – i.e. very low temperatures can be experienced
- Corrosion and material degradation and equipment impact
- Well Control procedures, kill and blowout risks

It should also be noted that as CO_2 is heavier than air, vent systems designed for methane on current drill rigs and platforms are not suitable for CO_2.

With these concerns the need for specialised drilling rigs and workover systems for infill drilling into a CO_2 charged reservoir, re-drilling, re-completion, workover and intervention, and plug and abandonment operations is being highlighted by operators, regulators and suppliers. Industry is taking up this challenge with solutions at various scales being developed.

Modular CO_2 Handling Package

Noble

Status: Under development

Website: Click here

Noble is developing a modular CO_2 handling package - a solution designed to safely process CO_2 during well control events. Unlike traditional well equipment and mud gas separator systems built for natural gas, this package accounts for CO_2's heavier-than-air behaviour, increased solubility, and extreme cold during decompression. The package is modular, rig-agnostic, and adaptable to drilling, workover, and relief well operations in CO_2-charged reservoirs. The package will incorporate:

- Electric Shut In Device installed below the traditional BOP
- Anti Joule Thomson Choke configuration
- Combined mud gas separator and degasser tank in one unit which avoids CO_2 in the return mud
- Alternative vent line that ejects CO_2 to the side and below the hull of the rig.

Noble is currently leading a JIP to take the project from conceptual design through manufacturing to deployment. They are expecting to begin prototype testing in 2026 and anticipate having units ready for commercial use by 2029.

AQC-CW Well Access Solution
Aquaterra Energy

Aquaterra Energy's AQC-CW intervention well access package is a field proven subsea to surface solution that allows safe well access between the subsea or surface tree / wellhead and surface intervention pressure control equipment to support coil tubing, e-line or slick line operations. Materials and components can be configured to suit various fluid, gas, temperatures and pressure ranges making CO_2 storage site subsea and surface intervention a reality.

Status: Commercially available
Website: Click here

As well as specialised drill rigs, companies are also looking to develop lower emission rigs running on clean fuels or renewable power and utilising higher levels of automation.

Moss CS ECO-X™
Moss Maritime

The Moss CS Eco-X™ is a semi-submersible drilling platform that builds on the proven CS-series with the advantage of digitalisation and automation technologies to increase operational efficiency. The aim is to offer a design with limited to no emissions. This is achieved through a hybrid power system, exhaust cleaning, the introduction of clean fuels and a plug in option. The CS ECO-X™ concept can be optimised for drilling wells for offshore CO_2 storage. Moss Maritime state (in the Global CCS Institute 2025 report (pg.246)) that it is ideally suited to the drilling of CO_2 injection wells due to:

- Reduced unit size and cost
- Maximised and flexible deck space with flush working deck/drill floor
- Modularised solutions
- Alternative (clean) fuels
- Automated and remotely operated equipment
- Minimum manning

Status: Under development
Website: Click here

Sea Swift CO_2 Platform Solution
Aquaterra Energy

Sea Swift is Aquaterra Energy's flagship intelligent platform solution that can be tailored to projects in oil and gas, CCS, offshore wind, and hydrogen generation. The platform topsides can be easily modified to include the required components such as CO_2 compressors and storage infrastructure designed to withstand the specific properties and behaviour of CO_2. The platforms have been delivered with 100% renewable power systems, eliminating the need for diesel generators or grid connections.

Status: Commercially available
Website: Click here

In addition to the drilling unit developments, several institutions are working on CO_2 well control applications, with research and industry partnerships. These include:

eDrilling
Development of specialised well control software tailored for CO_2 storage wells, handling risks like CO_2 kicks, blowouts, and cooling effects.

AGR
- Conducted assessments of well control tools for CO_2 wells, focusing on adapting existing simulation software to accurately model CO_2 thermodynamics and assist in planning contingency strategies.
- Supported Northern Lights CCS project by analysing equipment and workover operations for CO_2 injection wells, emphasising controlled bleed-off procedures and intervention systems.

Welltec
Offers advanced well completion and intervention solutions designed for CO_2-resistant long-term well integrity, such as their Annular Barrier (WAB®) technology, used in projects such as Greensand CCS (Denmark).

Universities

Universities working on CO_2 well control
- Heriot Watt University
- Texas A&M
- Louisiana State University (LSU)

Well control in CCS wells is a critical issue due to the potentially severe implications for both personnel safety and the reputation of the CCS industry should a significant incident occur. As more infill wells are drilled into charged reservoirs and interventions occur in active CO_2 wells, appropriate well control and CO_2 handling equipment is essential. This equipment must be fully tested and validated, both as individual components and whole systems, to confirm their capability to address the unique challenges posed by CO_2, including rapid temperature drops as discussed within section 4.1. Additional unforeseen challenges that require technological solutions will likely emerge as further CCS wells are drilled and worked over.

4.2.2 CO_2 Wells Intervention Equipment

Well intervention and workover equipment has existed for decades in the oil and gas industry, both for onshore and offshore wells, where conventional systems such as slickline/wireline, coiled tubing and snubbing are combined with specialised bottom hole assemblies (BHA)'s. Traditional workover and intervention equipment developed and proven for oil and gas applications are plentiful and too many to mention in this report. Instead a number of technologies stated for use for CO_2 wells intervention and workovers are highlighted including those that can be used for the remediation of legacy oil and gas wells, converting them to CCS wells.

As mentioned in the Intervention and Workover introduction (4.2) one aspect that must be considered when running well intervention equipment in CCS wells is the presence of CO_2 or CO_2-enriched fluids in the well.

Octopoda
Expro

Expro's Octopoda® is an oil and gas field proven, compact, modular, rig-less annulus intervention system designed to diagnose and restore well integrity and production by addressing issues such as sustained casing pressure (SCP) caused by gas or fluid migration within one of the well's annuli. The systems can be deployed to remediate leaks and also remove and replace corrosive annular fluid.

Status: Commercially available
Website: Click here

ReLine – expandable casing & tubular patches
CORETRAX – An Expro Company

Coretrax ReLine systems, which is corrosion resistant and gas tight, can allow for existing oil and gas wells to be converted to CCS wells, eliminating the need to drill new dedicated wells.

The ReLine systems are expandable casing and tubular patches which can be utilised for well integrity remediation, corroded tubing remediation and isolating specific zones. A key benefit of the ReLine system is that it has been designed not to restrict the ID of your well.

Deployed extensively for oil and gas applications with over 48,000ft of patches installed to address casing leaks and corrosion (case studies), it has also been deployed on a CCS project in Canada.

Status: Commercially available
Website: Click here & Click here

M-Bubble Sealing Solutions
dti

dti offer their M-bubble sealing solutions. These advanced sealing solutions enable the repurposing of oil and gas wells for CCS purposes by enabling permanent plugging of the lower completion to allow for safe workover/recompletion operations.

Status: Commercially available
Website: Click here & Click here

The following case study from Halliburton demonstrates how two legacy oil and gas technologies have been used together to provide an integrated barrier monitoring system used during well intervention work on a CO_2 injection well.

Case Study

Operator improves well intervention efficiency using integrated barrier-monitoring system

Tools used

EVO-Trieve® retrievable bridge plug with DynaLink® telemetry system

Overview

During a well intervention for a major operator, Halliburton delivered a wireless barrier monitoring solution that allowed pressure tests and verification in real time. This marked the first global installation of an integrated barrier system that combines the EVO-Trieve® retrievable bridge plug with the DynaLink® wireless acoustic telemetry system.

Challenge

The operator needed to complete well intervention operations, which included removal and installation of the Christmas tree on a CO_2 injection well. This required a verified shallow-set barrier to secure and control the well.

Link:
[Barrier Monitoring System enhances well intervention]

Solution

Halliburton teams from Testing and Subsea and Completion Tools recently began collaboration to develop an integrated barrier system that provides a reliable barrier using the EVO-Trieve retrievable bridge plug and wireless monitoring and verification using the DynaLink telemetry system. After meeting with the operator and careful consideration of the operational objectives, Halliburton recommended installation of a 4-1/2-in. EVO-Trieve retrievable bridge plug equipped with a DynaLink system single quartz gauge. The bridge plug/gauge combination was installed below the tubing hanger and pressure tested. A DynaLink system repeater with surface wireless kit was mounted onto the wellhead base and the signal sent to the data acquisition unit located in an air-conditioned container.

Result

Through collaboration between product service lines, Halliburton delivered a reliable technology-driven solution that allowed the operator to monitor shallow barrier integrity wirelessly and maximize asset value. Access to real-time data and diagnostics mitigated risks to personnel working in the well bay area, enabled quicker decision making, and helped eliminate uncertainty with pressuring up gas volume to conduct a positive test. Additionally, the barrier monitoring system provided valuable data before equalization and retrieval of the bridge plug.

4.2.3 Intervention Integrity Evaluation

The requirement for intervention or remediation to restore well integrity is assessed by monitoring operational performance to detect anomalies which could indicate loss of well integrity. In the case of shut-in or abandoned legacy wells, where operational performance cannot be used, tools must be run to assess the integrity of the well and assist in the decision as to whether well remediation and/or intervention is necessary. Fortunately, specialised technology to determine the cause of loss of well integrity and to assess overall well integrity have been developed over many years where similar challenges have needed to be address in oil and gas well performance and abandonment. Typical well integrity evaluation methods, using specialised tools run in the well, include diagnostics of tubing and casing, including leak testing, as well as wall thickness evaluations, fluid composition analyses and metallurgy evaluations. Cement evaluations are also important when validating the performance of plugs or annular cement. The types of intervention-based integrity evaluation can be broken down into:

- Well integrity diagnostics
  - Acoustic technologies including noise logging
  - Thermal logging for leak detection
  - Cement bond logs (CBL) and ultrasonic imaging tools for cement evaluation (USIT)
  - Calipers and direct tubular wall thickness measurements
- Reservoir optimisation and injection integrity evaluations
  - Tracers
  - Downhole intervention based injectivity testing

Many of these intervention integrity evaluations are available through traditional oil and gas technologies and service providers and are not listed in this section. A select few have been included.

SecureView® - Cased hole well integrity monitoring

Weatherford

Weatherford's SecureView® casing and cement evaluation service provides high-definition logs of inner casing, outer casing, cement strength, and cement bond which can reveal casing and cement anomalies and wellbore problems quickly and efficiently.

Comprising of a suite of well-diagnostic technologies (UltraView®, BondView®, FluxView®, and CalView®) the SecureView service combines and overlaps measurements gathering comprehensive data to detect any wellbore problems in one logging run.

Weatherford

Status: Commercially available

Website: Click here

PowerFlex/PowerEcho – Annular barrier evaluation service

SLB

PowerFlex™ and PowerEcho™ annular barrier evaluation services, part of the Sequestri carbon storage solutions family, significantly extend the operating range of ultrasonic cement and casing measurement to provide certainty for drilling, cementing, well integrity evaluation, and well abandonment operations. Their annular evaluation capabilities accurately quantify cement condition and bond for any slurry system, from ultralight foam cements to heavyweight blends, including contaminated and alternative barrier materials.

Providing rapid screening with results within two hours of pulling out of hole, PowerFlex service delivers high-resolution mapping of pipe thickness and cement with full azimuthal coverage. It also uniquely images the outer wall for pipe standoff. PowerEcho service, used for more conventionally constructed wells, also provides a high-resolution map of pipe thickness and cement.

These services are designed to perform reliably in extreme environments—including wells with heavy drilling fluids up to 19–20 lbm/galUS, large casing sizes up to 26-in. OD, and wall thicknesses of 1.25 in. and above—while still delivering azimuthal resolution down to 5°. Together, they provide robust and reliable data to quantify annular content and bond status and to confirm centralization and casing condition under even the most challenging well conditions

Status: Commercially available
Website: Click here

Epilogue

SLB

The Epilogue dual-string barrier evaluation service, part of the Sequestri carbon storage solutions family, combines wireline-conveyed, deep-array multimode sonic (0.5–20 kHz) and multimodality ultrasonic (100–500 kHz) measurements. The low-frequency sonic data enable evaluation of the B-annulus, while the ultrasonic measurements go beyond conventional monopole sonic tools by providing pipe-to-pipe standoff and A-annulus fluid characterization.

By integrating multimode sonic with multimodality ultrasonic measurements, Epilogue delivers radial coverage and azimuthal mapping of the B-annulus. For CCS wells, this capability allows cement evaluation through tubing without the need to pull completion.

With Epilogue dual-string barrier evaluation, both the A- and B-annulus can be assessed in a single run, eliminating the requirement to remove the inner pipe or tubing. This innovation reduces intervention rig time, operational cost, and carbon footprint, while ensuring reliable long-term barrier verification in CO_2 storage applications.

Status: Commercially available
Website: Click here

04
CCS Wells Technologies

4.3 Monitoring

A robust, risk-based monitoring program is essential to ensure that injected CO_2 remains securely stored, and CCS wells are the primary interface for verifying subsurface performance throughout the project lifecycle.

CCS depends on effective monitoring to demonstrate storage performance, manage risk, and maintain regulatory and stakeholder confidence over decades of operation. Monitoring provides evidence of modelled behaviour in the subsurface, confirms storage security, and enables timely intervention if anomalies or irregularities arise. Within this framework, CCS wells serve as critical access points to the reservoir and sealing formations, enabling high-fidelity measurements that underpin assurance of conformance, containment, and contingency readiness.

Wells represent both the primary pathway for CO_2 injection and the most likely avenue for potential leakage, making well integrity and performance monitoring essential components of any CCS project. Unlike conventional hydrocarbon operations, CCS wells must maintain integrity in highly corrosive CO_2 environments over extended timeframes, often spanning decades after injection has ceased. The regulatory framework reflects this, with agencies such as the US EPA's Class VI regulations and European CCS Directive establishing stringent requirements for continuous well monitoring throughout project lifecycles. These regulations mandate that monitoring plans must demonstrate both containment (no leakage) of CO_2 and conformance with predicted storage behaviour, requiring integration of well-based monitoring data with broader subsurface surveillance programs.

The Critical Role of Well-Based Monitoring

As already highlighted, well-based monitoring serves multiple interconnected objectives within the broader MMV framework:

Containment verification - demonstrating absence of CO_2 migration from intended storage zones

Conformance assessment - validating that injection operations align with predictive models

Assurance - providing stakeholders with evidence of safe storage performance

These objectives require monitoring systems capable of detecting anomalies at the earliest possible stages, before irregularities become significant enough to compromise storage integrity or require extensive corrective measures.

Evolution of Downhole Monitoring Technologies

The deployment of monitoring technologies within CCS wells has evolved significantly, incorporating innovations from both traditional oil and gas operations and purpose-built solutions for CO_2 storage environments. While there are many technologies which can be used from traditional oil and gas operations the monitoring objectives and operating conditions are different between oil and gas and CO_2 storage meaning that these technologies need to be tested and adapted for their new environment.

Modern well-based monitoring systems integrate multiple complementary technologies, including high-resolution pressure and temperature sensors, distributed temperature and acoustic fibre-optic sensing systems (DTS/DAS), chemical tracer technologies, and advanced logging techniques. These systems provide continuous, real-time data acquisition capabilities essential for early detection of potential integrity issues or unexpected CO_2 behaviour.

The selection and deployment of specific monitoring technologies will be site-specific and risk-based, considering factors such as geological conditions, well design parameters, corrosion potential, and regulatory requirements. Injector and dedicated monitoring wells can be fitted with sensors and logging systems that continuously track reservoir pressure, temperature, and fluid composition in real time. These measurements are used to validate injection limits, verify caprock integrity, and detect early signs of undesired migration or well barrier degradation. Legacy hydrocarbon wells within the storage complex also require focused surveillance, as they can constitute preferential leak pathways if not properly assessed and remediated.

As the CCS industry continues scaling toward commercial deployment, the lessons learned from test and demonstration projects such as Quest, active storage programmes such as Sleipner, and next generation projects like Northern Lights, Greensand, and Northern Endurance continue to refine best practices for well-based monitoring implementation. The success of future CCS deployment will depend significantly on the industry's ability to implement fit-for-purpose, cost-effective monitoring systems that provide the necessary assurance of long-term storage security while supporting the economic viability of large-scale carbon storage operations.

This part of the report will focus on well-based monitoring technologies and will highlight both existing and emerging technologies in the key areas of well integrity monitoring, injection monitoring and near wellbore formation and CO_2 plume monitoring. A summary of the different monitoring purposes, associated equipment, advantages, limitations and technical maturity is provided in table 7.

Information on monitoring techniques across the wider storage complex will not be covered within this report with the reader directed towards a comprehensive study undertaken by the North Sea Transition Authority (NSTA) on the role of MMV in CCS projects[16].

[16] spatial-coordination-project-_nsta_final-for-publication-august-2022.pptx

Monitoring purpose	Description	Monitored Zone	Equipment	Risk Category	Advantages	Limitations	Technical maturity	Suitable for Subsea CCUS	Operations & Maintenance	Decommis-sioning / Post-decom-missioning
Annulus Pressure testing	Tests designed to pressure annulus space and measure pressure drop to ensure well integrity and prevent casing leaks	Near-Surface/ Reservoir, Wellbore system	Pressure gauge on wellhead	Contingency, Mitigation	Direct test, low-cost	Limited to well system, not continuous test	mature	Y	Y	N
Casing Inspection logs	Downhole survey of well materials for indication of defects	Surface/ Near-Surface/ Reservoir, Wellbore system	Calliper, flux, sonic, EM, or noise logging tool	Containment	Straight forward test, can show precursors of corrosion, failure	Periodic test, well must be shut-in, interrupts operations	mature	Y	Y	N
Casing pressure monitoring	Monitoring pressure on casing annulus for casing leaks	Surface/ Near-Surface/ Reservoir, Wellbore system	Annulus pressure system and pressure gauge	Containment	Direct test, low-cost, often regulatory requirement	Limited to well system, does not provide location of defect	mature	Y	Y	N
Cement bond logging	Acoustic log that provides evaluation of cement/ casing to measure well integrity and zonal isolation	Surface/ Near-Surface/ Reservoir, Wellbore system	Wireline vendor and service rig	Containment	Simple quantitative method for analysing cement quality and inferring compressive strength	Limited to only evaluating cement bonding to the casing. Does not provide imaging between cement and formation. Does not evaluate low density cement.	mature	Y	Y	Y
Corrosion Monitoring (well materials)	Inspection to detect corrosion of well materials	Surface/ Near-Surface/ Reservoir, Wellbore system	ultrasonic, and electromagnetic tools	Containment	Straight forward test, can show precursors of corrosion, failure	Periodic test, well must be shut-in, interrupts operations	mature	Y	Y	N
Distributed Acoustic Sensing (DAS)	Laser light pulses from permanent or temporary downhole fibre optic cables. Seismic profiling that measures reservoir and caprocks to determine structural changes due to CO_2 injection and reservoir integrity	Surface/ Near-Surface/ Reservoir, Proximal to wellbore	Vendor, fiber optics, onsite data acquisition	Capacity, Containment, Mitigation	Provides continuous monitoring of the well site and can be used to detect changes due to CO_2 injection	A large amount of data is produced from this technology and requires extensive and costly processing. Can cause integrity issues if not installed correctly, fibre durability	mature	Y	Y	N
Distributed Temperature Sensing (DTS)	Fibre optic cables that measures changes in temperature to detect/ monitor temperature indicators of CO_2	Surface/ Near-Surface/ Reservoir: Proximal to wellbore	Vendor, fiber optics, onsite data acquisition	Containment, Mitigation	Provides continuous temperature monitoring and migration CO_2	A large amount of data is produced from this technology and requires extensive and costly processing. Can cause integrity issues if not installed correctly, fibre durability	mature	Y	Y	N
Distributed Pressure Sensing (DPS)	Fibre optic cables that measures changes in pressure to detect/ monitor preesure indicators of CO_2	Surface/ Near-Surface/ Reservoir: Proximal to wellbore	Vendor, fiber optics, onsite data acquisitio	Containment, Mitigation	Provides continuous pressure monitoring and migration CO_2	A large amount of data is produced from this technology and requires extensive and costly processing. Can cause integrity issues if not installed correctly, fibre durability	emerging	Y	Y	N
Downhole pressure/ temperature	Continuous temperature and pressure measurements to monitor reservoir integrity and CO_2 migration	Reservoir	Permanent downhole guages. EM wireless tools	Injectivity, containment, contingency, mitigation	Continuous in-place monitoring,	Gaskets can corrode over time and cause gauge malfunctioning, Battery life for long term monitoring	mature	Y	Y	Y
Geophysical Pulse Neutron Capture logs	Measures wellbore fluid saturation (oil/gas/water), changes and identifies CO_2 breakthrough and is used to analyse wellbore integrity	Surface/ Near-Surface/ Reservoir, Wellbore	Wireline vendor and service rig	Capacity, Containment	Fluid saturation of cased wells, porosity indicator, can show porosity changes near wellbore which can be used to indicate potential wellbore integrity	Reduced sensitivity in low-porosity or thinly bedded formations. challenges in distinguishing CO_2 from residual hydrocarbons	mature	Y	Y	N
High resolution acoustic imaging	Acoustic full-waveform sonic measures and images structural features and changes that occur due to CO_2 injection	Reservoir, Wellbore	Wireline vendor and service rig	Containment, contingency, mitigation	Direct imaging and monitoring of borehole structures and changes due to CO_2 injection	susceptible to borehole rugosity/washouts which will create poor quality images.	emerging	Y	Y	N
Microseismic/ Seismic Activity Monitoring	Passive technique for monitoring and identifying downhole fractures and microseismic events	Surface/ Near-Surface/ Reservoir: Reservoir and above	Downhole arrays (accelerometers, geophones. DAS)	Containment, Contingency	Critical technology for tracking induced seismicity and verifying geomechanical stability of reservoir and caprock. Real time surveillance provides early warning of injection induced faults and creation of potential leakage pathways	Moderate changes in dip perturbation or velocity changes can cause errors in velocity models. Low and high frequency signals can affect mechanism inversion.	mature	Y	Y	N
Operational Monitoring	CO_2 injection flow rates, pressure, temperature, density, composition monitoring	Reservoir	Gauges and flowmeters	Capacity, Injectivity	Accurate, robust, real-time;	Calibration gaps; data integrity under long-term CO_2 exposure; transient or multiphase flow accuracy issues	adapting for CCS	Y	Y	N
Tracers	Specially chosen chemicals added to CO_2 to 'label' its movement, allowing tracking and erly detection of migration from storage complex	Surface/ Near-Surface/ Reservoir	Soil gas monitoring points, gas collection equipment	Containment, contingency, public acceptance	Direct measurements, simple technology, high visibility, easy to communicate	Requires careful sampling, dilution and dispersion, false positives possible	emerging	Y	Y	Y
Vertical seismic profiling (VSP)	Seismic adata providing high resolution imaging of near wellbore to track CO_2 plume movement, leakage and changes in subsurface properties	Surface/ Near-Surface/ Reservoir, Proximal to wellbore	downhole receivers and surface sources	Capacity, Containment	Site characterisation prior to injection and time-lapse monitoring to survey migration of CO_2 plumes. Identification of potential fractures and faults in the subsurface.	Presence of hydrocarbons, limited spatial coverage away from wellbore, high cost	mature	Y	Y	Y

Table 7. Summary of monitoring purposes, associated equipment, advantages, limitations and technical maturity. Adapted from appendix 2 from the "ccus & offshore wind overlap study report"[17]

[17] CCUS & offshore wind overlap study report

4.3.1 Injection Monitoring

Accurate flow monitoring is essential for verifying injection volumes, optimising injection strategies and ensuring mass balance calculations for storage assurance over the lifecycle of CCS projects. Mass flow, density, composition, temperature and pressure measurements are commonly used to monitor injection at the wellhead.

Technologies to measure these parameters are relatively mature with temperature and pressure gauges widely available and will not be discussed further in this section. Flow meters such as Coriolis, ultrasonic, or differential pressure types are typically used to measure mass flow providing high-accuracy, real-time measurements. However, they are less technically mature for use in CCS with challenges around calibration, validation, and data integrity and durability with long term exposure to CO_2 and expected flow rates to assure compliance over the operational lifespan of CCS projects.

Subsea Venturi (differential pressure) meters have been selected and installed at each wellhead to monitor CO_2 injection rates for the Northern Lights CCS wells and were also installed for the recent Perenco Poseidon CO_2 injection test. Venturi meters were selected due to their proven robustness, suitability for high-pressure and variable-phase service, and proven performance in multiphase and supercritical CO_2 conditions. Venturi meters provide reliable, continuous flow measurement under harsh subsea conditions, have a low pressure drop, no moving parts, and maintain accuracy across gas, liquid, and supercritical CO_2 states, key for CCS operations where phase transitions can occur frequently.

However, although mature technology, gaps exist. Common challenges to all types of flow meter include real-time flow accuracy during transient or multiphase CO_2 injection (especially phase changes near critical points), long-term reliability under corrosive, high-pressure environments, and the need for universal, field-proven calibration under CCS-specific operating conditions. No single flow meter offers optimal performance under all CCS conditions, highlighting the importance of meter selection, system integration, and the development of advanced diagnostics and calibration workflows.

Carbonstream Subsea and Topside CO_2 Flow Meter
Solartron ISA/Ametek

The Carbonstream Subsea and Topside CO_2 Flow Meters, manufactured by Solartron, is a specialised Venturi-based flowmeter engineered for both subsea and topside CCS applications. The robust design, field-proven performance in harsh subsea conditions and its capability to measure pure, supercritical, or multiphase CO_2 flows with exceptional accuracy and minimal pressure drop qualities make it applicable for monitoring CO_2 injection and transportation in CCS projects.

Status: Commercially available
Website: Click here

4.3.2 In-well and Bottom Hole Monitoring

The primary purpose of in-well and bottom hole monitoring in CCS wells is to ensure the long-term safety, integrity, and effectiveness of CO_2 storage by verifying that injected CO_2 is securely contained within the designated geological formation and does not leak through engineered (wells) or natural (subsurface) pathways. These monitoring activities provide direct, real-time data on the operational and structural condition of the well, enabling operators to detect early signs of barrier degradation, leakage, or abnormal subsurface behaviour.

In-well monitoring focuses on continually assessing the integrity of critical well components, including casing, cement, and wellhead systems, to prevent loss of zonal isolation, fluid migration, or corrosion-related failures, risks that are heightened in the harsh, CO_2-rich environment typical of CCS operations. By monitoring bottom hole pressures and temperatures, operators can track the phase state and movement of injected CO_2, validate reservoir modelling predictions, and ensure injection is conducted within safe operational parameters. Together, these measurements enable early intervention in the event of leaks, meet stringent regulatory requirements, and support the efficient management and stewardship of CCS sites over their full operational and post-closure lifespans.

In-well monitoring techniques for assessing well integrity and bottom hole measurements in CCS wells integrate established and emerging technologies. Current industry-standard methods include cement bond logging and ultrasonic imaging for evaluating cement-to-casing bonding and detecting annular channels, multi-finger calipers and electromagnetic tools for quantifying casing deformation and corrosion. These are all provided by the major energy service companies, a couple of examples of which were provided in section 4.2.3, and specialised vendors providing a comprehensive portfolio of integrity monitoring solutions.

Nusonix
Cereus Energy Ultrasonics

Nusonix, developed by Cereus Ultrasonics, is an advanced acoustic (ultrasonic) well integrity and cement evaluation tool known for its ultra-high fidelity direct measurement technique. Its combination of extremely high-resolution data acquisition, down to 0.1 mm wall thickness accuracy and defect detection as small as 2 mm, with a compact, lightweight form factor allows deployment through tubing and multiple casing strings, including smaller and older wells. Unlike traditional cement bond logging (CBL) tools, Nusonix uses a broadband frequency (up to 2.5 MHz) for direct time and frequency domain analysis, providing true, contact-free imaging of internal diameter, wall thickness, and 360° cement bond with fast on-site reporting (within hours).

For CCS wells, Nusonix is particularly relevant as it enables rigorous, high-resolution inspection of tubular and annular integrity, early detection of micro-annuli and casing deformation, and detailed cement bond assessment, without requiring tubing removal or mechanical intervention.

Status: Commercially available
Website: Click here

Permanent Downhole Gauges (PDHG) are another mature technology with multiple vendors now adapting and designing PDHGs for CO_2 wells.

These systems are usually integrated where data can be transmitted via a wired or wireless telemetry to surface for real-time surveillance.

In wells where permanent gauges are not available or cannot be installed, periodic wireline deployment can be used to provide a snapshot of pressure and temperature profiles, supporting trend analysis and baseline establishment.

Time-lapse pulsed-neutron logging is also employed to monitor saturation changes, providing additional verification of hydraulic integrity.

DataSphere® Array CS, DataSphere® Opsis CS and DataSphere® Fiber CS - Permanent Downhole Monitoring Solutions

Halliburton

DataSphere® Array is designed for multi-zone reservoir and wellbore monitoring. With up to 50 miniature quartz pressure/temperature sensors along a single tubing-encapsulated conductor it provides mass distributed sensing for high-resolution mapping, enabling dense real-time profiling of temperature and pressure through cement, especially useful for monitoring across multiple zones and high-complexity completions

DataSphere® Opsis is a single-point gauge solution. Using highly reliable, resonating quartz crystal sensors for continuous, real-time pressure and temperature, the Opsis permanent downhole guage provides measurement at specific locations, such as the heel or toe of the well. Able to integrate with SmartWell completions and fibre-optic sensing the Opsis guage can be part of an integrated monitoring solution providing long-term integrity assurance at critical well points.

DataSphere® Fiber CS Fiber-optic monitoring allows vertical seismic profiling (VSP), micro-seismic monitoring (MSM), and the assessment of external and internal mechanical integrity testing (MIT) of wellbores. Trigger events that indicate containment risk are derived in real time from distributed acoustic sensing (DAS), distributed temperature sensing (DTS), and distributed strain sensing (DSS).

HALLIBURTON

Status: Commercially available
Website: Click here & Click here

Metris Evolve/Extreme/Express

SLB

SLB's Metris Evolve, Extreme, and Express, a part of the Sequestri carbon storage solutions family, are a suite of permanent downhole pressure and temperature gauges engineered for robust, real-time surveillance in the most demanding environments, including CCS injection and monitoring wells. They were qualified per API 19E for an operating temperature of -35 to 125°C, with an additional 100 thermal cycles, and survival temperature down to -78.5°C, and calibrated for 15 - 10,000psi pressure range at the operating temperature window.

Their multidrop architecture allows up to 16 dual-sensor gauges (32 total) deployed on a single monoconductor cable, greatly simplifying installation and enabling simultaneous, high-fidelity monitoring of multiple locations (tubing or annulus) in complex wells.

For CCS wells, these gauges deliver continuous annular and reservoir pressure/temperature data needed for leak detection, well integrity assurance, regulatory compliance, and injection optimisation. Their modular, resilient design supports fast retrofitting and scalable deployment, key for the long, high-integrity service required by CCS monitoring.

slb

Status: Commercially available
Website: Click here

Electromagnetic (EM) wireless technologies offer an alternative to measure temperature and pressure and are being increasingly considered for CCS wells. Installed within tubing or casing they offer real-time, cable-free data transmission from downhole sensors to the surface, especially valuable in high-pressure, high-CO_2 environments and for retrofitting legacy wells. Organisations such as Metrol, Expro, Emerson and Acoustic Data, amongst others, are recognised as providing advanced electromagnetic and wireless services along with the other major service operators.

Roxar™ Downhole Wireless System

Emerson

The Roxar™ Downhole Wireless System from Emerson is a permanent monitoring solution providing real-time, continuous pressure and temperature data from B-annulus or other critical well zones. A fully wireless transmission utilising a wireless reader and PT (pressure/temperature) transponder, the system transmits data through the well's metal barriers using robust, EM-based communication, maintaining the integrity of the primary and secondary barriers.

For CCS wells, the Roxar system provides continuous, retrofit-friendly monitoring of annular and barrier integrity, essential for early leak detection, pressure buildup warning, and long-term regulatory compliance. Its battery-free and non-intrusive installation maximises safety and data reliability in harsh subsea and CO_2-rich environments, making it ideal for both new storage projects and conversion of legacy wells to CCS monitoring.

EMERSON.

Status: Commercially available
Website: Click here

Paragon EM

Metrol

Metrol's Paragon EM is an advanced electromagnetic (EM) wireless telemetry system designed for permanent, real-time downhole monitoring of pressure and temperature in oil, gas, and CCS wells. It is able to deliver high-resolution, lossless digital data from multiple discrete points within the well without any downhole penetrators, cables, or in-well batteries.

For CCS wells, Paragon EM enables multi-year, near-real-time surveillance of critical annular and reservoir pressures at multiple reservoir and completion zones. Its wireless and modular installation allows for integration into both new and retrofit CCS completions and facilitates direct feedback on reservoir compartmentalisation and pressure front movement, delivering valuable operational and risk management insights over the decades-long lifecycle of a CO_2 storage site.

METROL.

Status: Commercially available
Website: Click here

SonicGauge

Acoustic Data

SonicGauge is a fully wireless downhole pressure and temperature monitoring system developed by Acoustic Data, relying on advanced acoustic telemetry to deliver real-time, high-frequency data acquisition for well testing, production, injection, and long-term reservoir monitoring. In CCS applications it supports continuous annular and reservoir pressure surveillance, integrity assessment, and early leak or barrier degradation detection. It is a cable-free, battery-powered gauge equipped with duplex (two-way) acoustic data transmission, deployable by slickline, e-line, or mounted externally on tubing, and capable of transmission through barriers, packers, plugs, and even in suspended or retrofitted wells.

SonicGauge can be installed in new or existing wells without requiring wellhead penetrations, downhole cables, or major interventions, and uses surface-mounted acoustic receivers (magnetically or via wellhead clamp) to decode and transmit downhole data to remote data systems.

Status: Commercially available
Website: Click here

CaTS EMX wireless monitoring system

Expro

Expro's CaTS EMX is a next-generation wireless monitoring system that leverages duplex electromagnetic (EM) telemetry to deliver real-time, long-duration pressure and temperature data from downhole sensors, without the need for cables, penetrations, or permanent modifications to the well. The ability to transmit data wirelessly through well tubulars, cement, and barriers, enables monitoring even in suspended or abandoned wells where traditional methods are impractical or impossible.

In CCS applications, CaTS EMX is highly valued for converting legacy, suspended, or abandoned wells into viable CO_2 monitoring assets capable of tracking reservoir and annular pressures, plume migration, pressure front movement, integrity, and leak detection throughout the full life cycle, including post-injection storage monitoring for regulatory compliance.

Status: Commercially available
Website: Click here

Metris Eclipse

SLB

SLB's Metris Eclipse, part of the Sequestri carbon storage solutions family, is a contactless B-annulus pressure and temperature (PT) monitoring system developed for continuous, high-precision surveillance of well integrity, especially in subsea wells and complex completions. The use of inductive coupler technology to transmit both power and data wirelessly between the gauge, mounted to the exterior of the production casing, and the tubing, enables real-time communication without breaching casing or tubing integrity. This slip-on, modular architecture streamlines installation and eliminates the need for through-casing penetrations or in-well batteries, dramatically lowering operational risk and long-term maintenance in harsh offshore or CCS environments.

Status: Commercially available
Website: Click here

DataSphere® LinX Monitoring System

Halliburton

DataSphere® LinX from Halliburton is a wireless, through-casing permanent monitoring system designed to deliver real-time pressure and temperature readings from behind casing or liner in the B-annulus of oil, gas, and CO_2 storage wells. The use of electromagnetic (EM) power and communication to enable continual sensor data transmission from behind well barriers allows it to operate without batteries, breaching casing integrity, or necessitating major well design changes. The system's EM transfer helps eliminate the limitations of conventional wired or battery-powered solutions, offering unlimited data transmission over the life of the well. This technology supports safer, more efficient operations and compliance in modern, multi-barrier wells, especially where annular monitoring is required but previously impractical or periodic.

Status: Commercially available
Website: Click here & Click here

Emerging technologies are extending surveillance capability by leveraging distributed acoustic sensing (DAS) and distributed temperature sensing (DTS) with fibre-optic cables, which provide continuous, high-resolution monitoring of acoustic and thermal anomalies that may indicate leaks, micro seismicity, or crossflows along the wellbore. Systems can be permanently installed in the wellbore or deployed using temporary or retrievable options.

While DAS and DTS offer the potential of turning the entire wellbore into a sensor there are challenges in processing and integration of the large amounts of data recorded to enable quick identification and response to potential well and reservoir anomalies. Expro have developed a complimentary suite of tools to enable close to real-time processing and visualisation of DTS and DAS data. eXtract software provides rapid decimation of the data, and the QikViewTM visualisation platform integrates and visualises the DTS and DAS data along with well logs, well design and operational data to enable fast and efficient interpretation and diagnosis of well and reservoir issues (Well_Intervention_-_DFOS_-_QikView.pdf).

Carina CarbonSecure

Silixa

Silixa's Carina CarbonSecure is a permanently installed, distributed fibre-optic sensing system purpose-built for carbon storage monitoring, leveraging the patented Carina Sensing System to provide ultra-high definition seismic, microseismic, temperature, and strain data in real time across the entire CO_2 storage lifecycle. Its engineered Constellation™ fibre, which delivers up to 20 dB (100×) greater signal-to-noise ratio compared to standard DAS, enables highly sensitive detection with fewer seismic shots, lower energy requirements, and smaller environmental impact.

Status: Commercially available
Website: Click here

ForeSite Sense

Weatherford

Weatherford's ForeSite® Sense is an advanced, modular reservoir monitoring system designed for permanent, high-reliability downhole surveillance in a wide range of well environments, including CCS injection wells. Its use of multiple high-resolution sensor types, optical, quartz, and piezo-electric, in a single cable, offers simultaneous, real-time measurement of pressure, temperature, acoustic/seismic signals, and flow across single and multizone wells.

The ForeSite® Sense optical monitoring system was deployed on the Perenco Poseidon CO_2 injection test. This advanced digital fibre-optic sensing system was deployed to oversee injectivity testing performance, providing real-time, high-resolution optical pressure and temperature data downhole to support monitoring and diagnostics during the CO_2 injection operations. The solution was integrated with other providers' technology, including Silixa's distributed fibre-optic acoustic monitoring, to deliver a comprehensive in-well surveillance and integrity assurance program for the duration of the test.

Status: Commercially available
Website: Click here

04
CCS Wells Technologies

SureVIEW CoreBright optical fibre

Baker Hughes

SureVIEW CoreBRIGHT enhanced backscatter fibre is a proprietary fibre-optic solution from Baker Hughes designed to deliver superior distributed acoustic sensing (DAS) performance for demanding environments including CCS wells. Utilising pure silica glass and engineered mechanical/chemical features for scatter enhancement, CoreBRIGHT fibre achieves industry-leading signal-to-noise enhancement (up to 30 dB) and is immune to hydrogen darkening, the primary failure mode for optical fibres in harsh environments.

Status: Commercially available
Website: Click here

Fli Dynamic De-Spool Probe

WellSense

An industry innovator in fibre-optic intervention, the Wellsense Fli Dynamic De-Spool Probe is a compact, single-use fibre-optic deployment tool designed to rapidly and cost-effectively deliver bare optical fibre into a well for distributed acoustic, temperature, and pressure sensing. By deploying fibre directly from a moving probe, rather than traditional wireline or slickline, the Fli system enables efficient, end-to-end fibre placement throughout the wellbore with precise depth control, minimal operational footprint, and no requirement for heavy equipment or winches. The system's single-use, disposable probe and fibre simplify operational logistics and reduce survey costs, making distributed sensing accessible and repeatable for well integrity, leak detection, cement assurance, and dynamic flow profiling for CCS wells.

Deployed for a leading integrated energy operator in Australia, it was the first time that fibre intervention has been used to survey live CCS wells and reservoirs.

Status: Commercially available
Website: Click here

Distributed Fibre Optic Sensing (DFOS)

Expro

Expro's Distributed Fibre Optic Sensing (DFOS) technology provides dynamic, high-resolution downhole monitoring using DAS and DTS sensing delivered via a thru-tubing fibre-optic enabled slickline or E-Line cable. Deployed through existing well completions without the need for costly workovers or permanent installation DFOS, coupled with proprietary eXtract and QikView software, can rapidly deliver real-time evaluation of flow, integrity, and leak signatures across the entire wellbore.

Status: Commercially available
Website: Click here

WellWatcher Neon
SLB

WellWatcher Neon's system enables ultra-high-resolution, real-time zonal profiling and dynamic leak detection using thermal and acoustic data. It is an integrated permanent reservoir monitoring system that uniquely combines fibre-optic DTS, DAS, and pressure/temperature (PT) gauges within a single permanent downhole cable combining both fibre-optic lines and an electrical conductor.

Each cable can accommodate up to three fibres: one dedicated to DTS, a second to DAS, and a third for an optical pressure gauge. The integrated electrical conductor simultaneously transmits data from downhole electronic PT gauges, delivering a comprehensive, high-resolution monitoring solution.

Status: Commercially available
Website: Click here

Next generation systems are investigating the inclusion of distributed pressure sensing (DPS). Aiming to achieve spatially resolved, real-time pressure data throughout the well, it is in early development and is commercially immature. Advanced analytics, such as machine learning for anomaly detection and improved log interpretation, are being introduced to integrate data from multiple sensor types and enhance diagnostic reliability.

Challenges and Technology Gaps

Significant challenges persist, including the need to balance spatial resolution and coverage, sensor durability and data stability in corrosive high-pressure CO_2 environments, and in achieving cost-effective, long-term monitoring especially for offshore storage sites and legacy oil and gas wells. While technologies exist for post-site closure monitoring they typically rely on utilising battery power. The latest batteries deployed can last upwards of 10 years but with the requirement to potentially monitor wells for decades after injection has stopped there is a need for further development of battery life and performance or other means of communication to prevent potentially costly remediation to replace batteries or monitoring systems.

Legacy oil and gas wells pose a significant challenge. Many lack modern monitoring infrastructure or there are concerns on their integrity, requiring innovative approaches for monitoring, retrofitting or abandonment. Aquaterra Energy and Sentinel are leading the way in this space developing innovative solutions to re-enter abandoned wells, discussed further in section 4.4.2, and provide long-term cost-effective monitoring of abandoned and active wells.

CO_2 Monitoring Platform
Aquaterra Energy

The Aquaterra subsea platform, specifically its CO_2 monitoring solution, offers an integrated system for long-term monitoring and integrity assurance of offshore CCS sites. The platform which can be positioned over or near the wellhead of active or legacy wells consists of a multi-parameter design combining permanent dissolved CO_2 sensors in the water column, customisable baseline environmental surveys, and sub-surface passive and active seismic arrays, all connected via self-powered (solar or wave) nodes for uninterrupted, remote data transmission between seabed and topside.

Status: In development
Website: Click here

WellSentinel
Sentinel Subsea

Wellsentinel is an innovative passive, power-free subsea well monitoring system engineered for continuous, long-term leak detection at wellheads, christmas trees, and related infrastructure, including CCS wells. It uses a proprietary chemical or material trigger mechanism that responds specifically to target materials, such as CO_2, present in the water around the wellhead. Detection initiates a fully mechanical release of a buoyant alert beacon to the ocean surface, where it automatically transmits a satellite message to asset owners, providing immediate location-specific notification of integrity breaches requiring no subsea data cabling, electrical power, or intervention requirements.

Status: Commercially available
Website: Click here

Key technology gaps include the commercial readiness of distributed pressure sensing and the integration of automated, cross-modal data integration to enable timely, risk-based decisions across the asset lifecycle. Robust monitoring plans will increasingly rely on a hybrid approach, combining high-TRL methods and innovative sensing technologies to deliver early detection, comprehensive well surveillance, and adaptive assurance strategies for CCS operations.

4.3.3 Near Wellbore Formation Evaluation and CO_2 Plume Monitoring

Wells and in-well monitoring technologies play a critical role in assessing near-wellbore formation damage and CO_2 plume migration through direct, high-resolution subsurface access that complements surface-based surveillance methods. These technologies enable real-time detection and time-lapse monitoring of geomechanical changes, fluid migration patterns, and containment integrity essential for safe CO_2 storage operations.

Vertical Seismic Profiling (VSP) in CCS projects is deployed to obtain high-resolution seismic images around injection and monitoring wells, enabling direct observation of CO_2 plume migration, reservoir changes, and potential leakage pathways. VSP surveys leverage downhole geophones and more recently distributed acoustic fibre-optic (DAS) sensors to acquire subsurface data with superior vertical and lateral resolution compared to surface seismic methods. However, VSPs provide limited coverage away from the well so other seismic or non-seismic methods are required for wider spatial imaging of CO_2 movement within the storage complex. Time-lapse VSP allows operators to track the evolution of the CO_2 plume, monitor caprock integrity, and calibrate geological models by repeatedly imaging subsurface changes as injection progresses.

Optiq and Optiq Seismic
SLB

SLB's Optiq and Optiq Seismic, part of the Sequestri carbon storage solutions family, are advanced fibre-optic monitoring solutions designed for continuous, high-resolution downhole surveillance, particularly for seismic and reservoir monitoring applications. Optiq fibre-optic platforms integrate DAS, DTS, and other distributed sensors in both permanent and temporary well deployments, enabling seamless, real-time data acquisition across multiple wells and installation types.

A deployment-agnostic DAS-based borehole seismic solution it eliminates the need for conventional downhole geophone arrays, transforming any fibre-enabled run, permanent or wireline, into a seismic acquisition opportunity. This innovation allows zero-offset, walkaway, 3D, and 4D VSPs to be rapidly acquired with increased spatial resolution in minutes, rather than hours or days, while reducing energy consumption, carbon footprint, and operational risk.

Optiq Seismic's simplified logistics, coupled with proprietary edge-optimised interrogation and cloud-native workflows, deliver answer products up to 18× faster than traditional methods, enabling operators to optimise imaging, monitoring, and decision cycles in real time, making it a uniquely efficient and flexible tool for CCS, seismic, and production monitoring.

Status: Commercially Available
Website: Click here

While DAS compared to traditional geophones have gained popularity due to its ability to turn the entire wellbore into a dense seismic array and enable continuous or intervention-free monitoring, geophones continue to be preferred for certain VSP applications that require high sensitivity, lower-frequency response, and superior vector seismic measurements (3-component data) not always achievable with current DAS systems.

In practice, many CCS projects may consider deploying both technologies in parallel or sequentially: geophone-based VSP for detailed baseline or calibration surveys, and DAS for frequent, operational, or long-term seismic surveillance. Their complementary strengths ensure that downhole geophones retain a crucial role in the VSP toolkit for subsurface monitoring.

Microseismic monitoring is a critical technology in CCS for tracking induced seismicity and verifying the geomechanical stability of the storage reservoir and caprock during and after CO_2 injection. By continuously recording small-scale seismic events with downhole arrays (geophones, accelerometers, and DAS) operators can detect, locate, and characterise fracturing, fault slip, and pressure transmission through the subsurface. This real-time surveillance provides early warning of injection-induced faults, reservoir compartmentalisation, and the potential creation of leakage pathways, supporting adaptive management and risk mitigation. Microseismic methods complement seismic imaging and wellbore measurements, providing continuous, high-sensitivity insight into dynamic reservoir behaviour essential for safe, long-term CO_2 containment.

Using the same fibre technology as discussed earlier it the report (Section 4.3.2) there are many providers of DAS integrated microseismic services such as Sintella and Optasense as well as those previously mentioned. One additional example is SLB's CCS Real-Time Induced Seismicity Monitoring (RT-ISM).

CCS Real-Time Induced Seismicity Monitoring (RT-ISM)
SLB

SLB's CCS Real-Time Induced Seismicity Monitoring (RT-ISM), part of the Sequestri carbon storage solutions family, is an automated, microseismic monitoring solution purpose-built for high-sensitivity, real-time detection and localisation of induced seismic events during CO_2 injection and long-term CCS reservoir management. Enabled by continuous fibre-optic DAS sensing, powerful edge computing, and seamless integration with permanent or temporary fibre installations, the compact system design allows rapid deployment with minimal operational footprint, and once installed, the sensor operates autonomously without further intervention. The user can access the system remotely and visualise data through the web-app.

Status: Commercially Available
Website: Click here

Pulse neutron logging is another technology that provides quantitative and time-lapse assessment of CO_2 saturation and fluid distribution in the near-wellbore region. This method uses a pulsed neutron source and gamma-ray detectors to measure neutron capture and inelastic scattering, which are sensitive to the hydrogen content, and therefore the type and saturation of formation fluids. In CCS wells, pulse neutron logs (PNL) are routinely applied to distinguish CO_2 from water or hydrocarbons and to monitor changes in reservoir saturation due to injection or migration. Time-lapse PNL provides critical insights into plume movement, detects CO_2 breakthrough, and helps confirm containment by highlighting shifts in thermal neutron capture values and formation fluid composition. The technology is highly mature and widely implemented, offering robust, through-casing surveillance without well intervention. A couple of examples are given below.

Raptor 2.0

Weatherford

Weatherford's Raptor 2.0 cased-hole evaluation system is an advanced pulsed neutron logging technology designed for high-resolution measurement of oil, water, and gas saturations behind casing. Comprising of a four-detector array it has greater sensitivity to gas saturation, a larger volume of investigation, and enhanced resolution compared to conventional two-detector tools. The Raptor system uses three logging modes. enhanced Sigma and Carbon/Oxygen techniques for oil-water saturation measurements in saltwater and freshwater formations, and a proprietary N-Vision™ technique to quantify gas-liquid saturation.

Weatherford

Status: Commercially available

Website: Click here

Pulsar

SLB

The Pulsar multifunction spectroscopy service, part of the Sequstri carbon storage solutions family, enables monitoring of CO_2 injection and storage through advanced pulsed neutron measurements. By combining multiple detectors with a high-output pulsed neutron generator, Pulsar provides stand-alone cased-hole formation evaluation, including fluid identification, saturation monitoring, and salinity determination behind casing. In CO_2 wells, Pulsar supports time-lapse surveillance programs to track the migration and distribution of injected CO_2, verify containment within the storage reservoir, and demonstrate conformance with regulatory requirements for CCS projects.

slb

Status: Commercially available

Website: Click here

Emerging technologies are advancing the precision and coverage of well-based monitoring. Distributed acoustic and temperature sensing is being expanded from permanent to intervention-based deployments, supporting retrofit in legacy wells.

Advanced tracer systems, using ultra-sensitive chemical markers, can provide a low cost and rapid detection solution for early warning of potential well or reservoir issues. Deployed through the well, tracer technology involves injecting uniquely identifiable chemical or isotope tracers alongside CO_2 to monitor its migration, verify reservoir conformance, and detect leaks or loss of containment with extremely high sensitivity. Tracers are selected for their chemical stability, detectability at ultra-low concentrations (down to parts per trillion), and behaviour that closely follows CO_2 movement in the subsurface. Once deployed, their presence is monitored at observation wells, or through sampling enabling early detection of CO_2 migration outside the storage formation or caprock integrity loss.

Recent advancements include the introduction of highly durable nanoparticle tracers (QuantumPro FloTrac), maintaining integrity and detectability in high-temperature, extreme subsurface environments, and providing permanent "signatures" for long-term site assurance. Ultra-sensitive detection methods down to 0.1 parts per trillion (ppt) (Resman High Integrity Detection System (HIDs)) are being developed, reducing the need for large quantities of tracer material therefore improving monitoring economics and sustainability. Hybrid monitoring frameworks now combine chemical tracer data with seismic and pressure/temperature measurements to provide a multi-layered, robust subsurface surveillance system, supporting regulatory MMV requirements over operational and post-injection periods of 30 years or more.

These advancements not only enhance early warning and rapid response to leaks but also improve monitoring and operational economics.

FloTracTM

QuantumPro Inc

FloTrac is QuantumPro Inc.'s advanced nanoparticle tracer technology featuring 220 unique, ultrahigh-resolution tracers specifically designed for CO_2 monitoring in CCS operations. Its high thermal durability, combined with indefinite signature stability, enables long-term CO_2 plume monitoring without repeated tracer injections.

FloTrac nanoparticle tracers are non-hazardous, non-intrusive, and compatible with both oil and water phases, making them ideal for complex multiphase CO_2 environments. Each tracer maintains a distinct, permanent signature that allows precise spatial characterisation of CO_2 distribution and movement within the reservoir, supporting optimisation of injection, storage, and containment strategies.

For CCS applications, FloTrac coupled with near-surface and seabed sampling, as well as integration with geophysical methods, enables comprehensive multi-well assessment, precise tracking of CO_2 plume behaviour and early detection of potential integrity failures and containment breaches.

QuantumPro, Inc.

Status: Commercially available

Website: Click here

High Integrity Detection System (HIDs)

Resman Energy Technology

Resman has successfully deploying tracer technologies and monitoring services for over 30 years.

Resman's High Integrity Detection System (HIDs) is an advanced tracer-based monitoring solution designed for leak detection and integrity assurance in CCS projects. Typically deployed in shallow boreholes around the injection site HIDs can detect CO_2 tracer concentrations down to 0.1 parts per trillion, significantly out performing detection limits of conventional pressure or gas-based monitoring methods. The system has been successfully deployed and is operational in Abu Dhabi's first CO_2 storage site focusing on monitoring near the injection well to verify caprock and well integrity, quantify leaks and pinpoint their source.

RESMAN® ENERGY TECHNOLOGY

Status: Commercially available

Website: Click here

Challenges and Technology Gaps

Key challenges and technology gaps persist for deploying VSP, microseismic, pulsed neutron logging, and tracer technologies in CCS projects, impacting their efficiency, coverage, and long-term reliability.

For VSP, limitations include high operational cost, logistical complexity, and reduced spatial coverage away from wells. While DAS VSP improves spatial resolution, fibre-optic durability and signal quality over the potential long period of operation (decades) remain a concern, and repeated surveys can be resource-intensive.

In microseismic monitoring, data quality is affected by noise, sensor coupling, and the complexity of locating small events in deep storage sites. DAS-based systems improve coverage but can lack the sensitivity and low-frequency response of geophones. Automating event discrimination between injection-induced microseismicity and natural background noise remains a technical gap, as does robust, real-time interpretation for prompt risk response.

Pulsed neutron logging faces reduced sensitivity for distinguishing CO_2 in low-porosity or thinly bedded formations, as well as interference from saline water or complex lithology, which can complicate saturation interpretation. There are also challenges in distinguishing CO_2 from residual hydrocarbons as CO_2 and methane both have low hydrogen index signals. Accurate interpretation requires good baseline data, careful calibration, advanced modelling and often supporting information from other logging method as in the method proposed by Kim et al[18] to distinguish CO_2 from hydrocarbon gas in depleted gas reservoirs.

Detecting small or diffuse saturations or resolving multiphase distributions remains challenging, and while the method is logistically mature, CCS-specific workflows for frequent, repeatable, and automated analysis are not yet fully optimised.

For tracer technology, technology gaps include ensuring long-term tracer stability, especially for novel nanoparticles or biomarkers, as well as avoidance of cross-contamination and maintaining accurate detection in dilute, dispersed migratory plumes. Sampling infrastructure can be limited in remote or offshore sites. Integration of tracer data with other monitoring results and regulatory acceptance for leakage quantification also require further development, while new tracers must be validated for environmental safety over the storage lifespan.

Across all methods, scaling field pilots to commercial, long-duration CCS projects, automating data integration, and assuring sensor or tracer durability in harsh CO_2-rich environments remain substantial industry challenges.

[18] Distinguishing CO_2 and Hydrocarbon Gas Using Pulsed Neutron Logs for CO_2 Storage Projects in Depleted Gas Reservoirs | SPWLA Annual Logging Symposium | OnePetro

4.3.4 Digital Technologies

While this report has focused predominantly on materials or equipment that can be used to construct or be deployed in CCS wells the increasing importance in the role of digital and AI technologies needs to be mentioned.

In a low-cost margin business such as CCS the use of AI and digital technologies can help to enhance operational efficiency and optimise project delivery through the integration of advanced modelling, acquisition of real time data, risk management and utilisation of digital twins to make informed proactive decisions across the CCS full value chain.

Halliburton (CO_2 Storage Suite) and Baker Hughes (CarbonEdge) are just a couple of examples of end-to-end digital solutions for storage site assessment, planning and management.

CO_2 Storage Suite
Halliburton

CO_2 Storage Suite provides industry-validated workflows designed for efficient and cost-effective CO_2 storage projects across multiple scales from basin screening, site characterisation, down to wellbore and completion simulation.

Status: Commercially available
Website: Click here

CarbonEdge
Baker Hughes

CarbonEdge™ is a digital solution designed to optimise CCUS operations across the full value chain. It integrates real-time data, predictive analytics and risk management to support, but not limited to, planning and execution of MMV plans from capture to long-term subsurface storage.

Status: Commercially available
Website: Click here

SLB also offer a plethora of digital solutions for CCUS designed to help screen, rank, design, model, simulate and analyse every phase of the CCS lifecycle. SLB's Olga dynamic multiphase flow simulator is the industry-standard tool for modelling to predict fluid properties and behaviours though the wellbore to help refine and limit design conditions.

While these solutions provide an integrated full value chain approach, tools are also being developed targeting specific challenges. One of these areas is well integrity assessment, especially for legacy wells, which is a vital element of any storage site appraisal.

As described earlier, wells and in particular legacy wells, represent a major risk to containment of CO_2 as they provide the most likely migration pathways to surface. Predicting the leakage risk of all legacy and future wells is therefore a critical part of the risk assessment process when selecting or ranking a depleted hydrocarbon field or saline aquifer for CO_2 storage. Historically a qualitative approach to well integrity assessment has been taken based on the available information which can vary in quantity and quality depending on the age of the well. The assessment of the well stock within the storage complex will have a significant bearing on its operation potentially dictating injection and MMV scenarios. This had led to the development of innovative quantitative approaches aimed at giving a measure of well integrity and its probability to leak. By adopting a quantitative risk-based approach, operators, regulators, and stakeholders can make better-informed decisions on safe long-term containment of CO_2 within the storage complex.

One such method has been developed by Heriot Watt University through the NZTC Open Innovation Programme. The project extended their existing P&A well design framework for hydrocarbon wells to provide a fully probabilistic quantitative risk-based framework for integrity assessment and well P&A design for new or legacy wells in CO_2 storage projects.

A Risk-Based Modelling Framework for Assessing Legacy Well Integrity in CCS
Heriot Watt

Heriot Watt has developed a fully coupled probabilistic risk based modelling framework to assess the integrity of CCS wells providing data based risk-analysis for improved MMV planning and regulatory compliance. The framework includes specialised modules that quantify the long-term impacts of CO_2 exposure on the integrity of key well components. These include a cement–CO_2 geochemical module to evaluate potential cement degradation and self-healing; a geomechanical module to quantify the wellbore defect sizes due to pressure and stress variations during CO_2 injection and post-storage conditions; and a corrosion module to quantify the significance of CO_2-induced tubular corrosion.

The framework has been applied and tested on a selection of wells from project partners taken from CCS licenses.

Status: Pre-commercial
Website: Click here

A similar approach has been adopted by Net-Zero Geosystems a UK-based technology company specialising in advanced simulation modelling for subsurface well integrity and risk analysis, focused on supporting CO_2 storage (CCS), hydrogen and fuel gas storage, geothermal, radioactive waste disposal, and oil and gas operations.

DRISCO$_2$Well
Net-Zero Geosystems

Net-Zero Geosystems has developed a robust, multi-scale predictive modelling software that combines reservoir-scale geomechanics (stress, pressure, induced seismicity) with defect-level simulations to forecast the probability and mechanisms of well integrity loss, including cement debonding, fracture development, and leakage potential, across the full well lifecycle. The company's simulation tools, such as those developed in the DRISCO$_2$Well project with support from TotalEnergies and the UK Department for Energy Security and Net Zero, deliver transparent, evidence-based risk analysis for new and repurposed CO_2 injection wells, optimising designs for cost, safety, and regulatory approval.

Status: Commercially available
Website: Click here

Further to these solutions a recently published report (Hardiman et al, 2023[19]) references the use of Peloton WellMaster Database along with Analyser software to calculate an overall well leakage probability and forms a good base for analytical modelling based on historical data for a substantial number of wells.

[19] Deep Geological Storage of CO_2 on the UK Continental Shelf: Containment Certainty: Supplementary Note C: Well Analysis Using Peloton WellMaster Database

Peloton Platform Well Integrity
Peloton Well Focused

Peloton WellMaster is a global well equipment reliability database that tracks failure frequencies and service records for over 6,000 wells and 70,000 well components across 34 operators worldwide. Its collection of real-world failure data for well barrier elements enables risk-based, data-driven design and operational decisions for both conventional and CO_2 storage wells.

Used through the Peloton platform its well integrity solution supports simulation of barrier and leak frequencies for primary and secondary well barriers, including casing, packers, and cement barriers helping operators benchmark reliability, anticipate failure rates, and fulfil regulatory containment assurance over multi-decade injection and post-closure lifecycles. Its analytics enable Monte Carlo modelling of leak scenarios, selection of best practices and equipment, and compliance with evolving CO_2 storage standards and requirements.

Status: Commercially available
Website: Click here

Specific software designed for CCS MMV integrating multiple data sources to provide comprehensive and real time well monitoring is available from numerous providers. An example is Halliburton's Visum®.

Visum® CS MMV Service
Halliburton

Visum® CS MMV Software is an advanced measurement, monitoring and verification (MMV) software, specifically designed for CO_2 injection projects. By integrating fibre optic technologies such as Distributed Temperature Sensing (DTS) and Distributed Acoustic Sensing (DAS) with data from pressure gauges, Visum software provides comprehensive, real-time well monitoring. The platform processes large datasets locally using GPU-powered edge devices, delivering immediate, actionable insights to ensure safe and effective CO_2 sequestration and storage. In alignment with local regulatory requirements, Visum software supports operators in achieving long-term CO_2 containment, providing critical evidence for compliance and enabling proactive decision-making throughout the well's lifecycle.

Status: Commercially available
Website: New product - contact Halliburton for further information

While this is only a small snapshot into the use of digital and AI solutions, it demonstrates the growing trend to leverage the wealth of data available and the power of digital technologies to link that data to provide valuable information which can shape and adapt monitoring plans throughout the lifecycle of the storage complex.

As had been demonstrated throughout the Monitoring section there are an abundance of technologies available and being adapted for use with CCS wells to allow a robust well based monitoring programme to be put in place helping to ensure that injected CO_2 remains securely stored. However, a key challenge is balancing the "perfect" monitoring programme with the economic landscape of CCS wells.

4.4 Legacy Oil and Gas Wells – Remediation Technologies

Well remediation is another key topic within the CCS wells landscape. Well remediation is primarily considered relevant for legacy oil and gas wells within CO_2 storage licenses, which may require repair or additional well isolation and/or plug and abandonment. This could be performed prior to CO_2 injection start-up or alternatively later in the projects' life if significant wellbore leakages are observed at legacy well sites. Should active injection or monitoring wells require repair or plugging, it is expected that they should be treated with well intervention and drilling technologies as described in section 4.2 in line with current oil and gas industry practice with potential additional CO_2 well control considerations.

Well remediation in CCS wells can be critical to ensure long-term containment and integrity for the entire storage license, by re-instating full wellbore isolation.

Key topics within well remediation include:

- Risk assessment of legacy wells, understanding and determining whether remediation is applicable
- Well access to legacy wells, where wellhead infrastructure has been removed
- Downhole remediation tools – open up for permanent barriers
- Downhole remediation tools – establishment of well barrier status (set plugs)
- Downhole remediation tools – verification of well barrier status
- Well interception / relief well

4.4.1 Risk assessment to evaluate whether legacy oil and gas wells require remediation

Outside of technology and deployment tools for well remediation, there is an industry gap related to the availability of one systematic, industry-wide risk assessment and acceptance criteria of wells, in order to determine whether well remediation of legacy wells is required. Numerous consulting firms and universities have developed qualitative well screening tools as well as detailed analytical models for assessing wellbore leakage risk including potential leak rates. In these models, the leak flow rates are often modelled based on flow theory, such as Darcy's law and more refined multi-phase flow analysis without direct measurements or indication as to the actual leakage rates, flows and volumes occurring downhole. For the analytical models, many of the inputs are highly uncertain and the uncertainty is often represented by Monte Carlo simulations, to best characterise the leakage risk including consequence and probability. When inspecting the risk outcomes from risk studies or analytical modelling, one very important challenge/gap is the interpretation of "no significant risk of leakage" – the thresholds and acceptance criteria, above which levels legacy wells (and CO_2 injection wells) require remediation, and proactive remediation, also in dialog with regulators. Currently, the industry lacks a clear definition of "no significant risk of leakage."

4.4.2 Access and Interception

For legacy well remediation, several of the primary technology challenges are related to well access and well interception (relief wells). Case histories are generally less documented in the industry, as operators are hesitant to share details of wells having had insufficient well integrity histories requiring remediation. Relative to well access and interception, the following considerations are relevant:

Well access to legacy wells, where wellhead infrastructure has been removed

Application
Re-enter and repurpose abandoned wells for CO_2 storage, re-connect to wellhead infrastructure both for onshore and offshore wells. Or re-enter to remediate or re-abandon if there are suspected integrity issues that need to be addressed prior to injection starting within the storage complex.

Technology
Vertical re-entry techniques, casing logging, and installation of pressure-retaining barriers below the mudline. Transition and wellhead re-connection tooling, such that rig systems, including well control systems are able to re-connect to legacy wells.

Challenges
Ensuring the connectivity to the legacy wells could be time consuming and an uncertain process. Various contingencies may need to be planned for, and cost uncertainties may be present, as well as uncertainties in the amount of kit needing mobilisation to the well site. Additionally, the location of legacy wells may be uncertain or unknown.

Similarities / differences to oil and gas wells technology
Remediation technology exists today and has been used historically on oil and gas wells globally, where well integrity challenges have required re-connection onto legacy wells. However, in these cases the wells would not have been fully abandoned and severed below the surface as is likely to be the case of some legacy wells which sit within CO_2 storage sites.

Well interception / relief well

Application
Intercept legacy wells with relief well technology to establish permanent well barriers at the proper plug depth or for other well integrity purposes.

Technology
Active and passing well ranging technology, intercept and wellbore re-entry.

Challenges
Intercepting the well at the correct position without jeopardizing the well integrity or near wellbore formation strength.

Similarities / differences to oil and gas wells technology
This technology exists today and has been used historically on oil and gas wells globally, for relief well application.

Generally, the equipment and technology for well remediation of legacy wells, once you have gained access, already exists and is very similar to oil and gas well remediation technology.

Intersecting and re-entering legacy wellbores via an intercept/relief well, in order to restore and re-instate well integrity and isolate towards CO_2 storage, is challenging and costly with one of the key challenges being locating the legacy wellbore. Numerous companies have technologies to assist with this. SLB's Well Radar and Halliburton's magnetic ranging solutions are provided as examples below.

Well Radar™
SLB

Well Radar™ ranging and interception services combine the technologies and expertise of multiple domains, including drilling, surveying, formation evaluation, geosteering, and reservoir mapping to deliver real-time ranging with precision. It implements advanced reliable rotary steerable technologies to enable higher performance drilling. Additionally, the services provide definitive dynamic surveys that deliver the industry's first passive magnetic ranging (PMR) -while-drilling for high efficiency, as well as the industry's first AMR 3D reservoir mapping-while-drilling service, superior data density, and ranging confidence.

Status: Commercially available
Website: Click here

WellSpot® Active Magnetic Ranging Service
Halliburton

Intercepting a well or drilling a relief well requires pinpoint accuracy to control the situation safely and efficiently. Halliburton's active magnetic ranging system provides the user with precise distance and directional data for well interception, regardless of their ability to access the target well. Because the user has the exact parameters needed to hit the target, they can gain access to the well and control of the situation successfully and safely. WellSpot™ active magnetic ranging service achieves an industry high success rate with over 300 well intercepts drilled over a four-decade track record.

Status: Commercially available
Website: Click here

In terms of companies with significant experience in drilling intercept/relief wells, Wild Well Control specialise in this.

Engineering and optimisation – Relief Wells
Wild Well Control

Wild Well Control has developed and executed the most challenging plugging, and isolation schemes. With the world's top team of Relief Well Experts, Wild Well offers relief well engineering, management, and design services to ensure proper planning and oversight for the safe and successful execution of the Relief Well Operation. These services include: Relief Well Intersection Management, Dynamic Kill Management, Wellsite Supervision.

Status: Used in projects
Website: Click here

In some cases relief well drilling could be infeasible. Another option for getting back on to well is excavation around the severed well however this could involve enormous amounts of material being removed with no guarantee of successful reconnection. Both the aforementioned options are also costly and due to the economics of the CCS industry cost is critical to the viability of a storage site. Aquaterra Energy have a proposed solution for vertical well re-entry utilising their patent-pending recoverable abandonment frame as part of their legacy well re-entry service which as a whole includes locating, re-entering and re-abandoning legacy wells.

Recoverable Abandonment Frame (RAF)
Aquaterra Energy

The Recoverable Abandonment Frame (RAF) is an innovative, cost-effective vertical well re-entry solution designed to reduce costs and project timelines. Aquaterra Energy state that the RAF could reduce abandonment costs by £20million per well and cut project timelines by 50%.

The RAF is a specially designed steel frame that can be positioned precisely over a well, enabling safe vertical re-entry. The frame provides structural support for all intervention equipment, keeping the weight off the well to avoid damaging any corroded casings. Its unique movement mechanism allows for adjustments to account for installation tolerances.

The RAF is intended for repeat use across multiple wells and locations and is modular in design for easy transport and quayside assembly.

In June 2025 Aquaterra Energy announced that they had won two landmark contracts for Northern Endurance Partnership (NEP), one of which will address the challenge of safely re-abandoning two legacy wells. Aquaterra Energy will deploy RAF as part of its Legacy Well Re-entry and Re-abandonment service.

Status: Commercially available
Website: Click here & Click here

05 Acknowledgements

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