REX-CO2

Deliverable D5.1

Recommendations for re-using existing wells for CO_2 storage

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Accelerating CCS Technologies

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Executive summary

This report provides a summary of the key findings of the REX-CO_2 project and recommendations for re-using existing oil and gas wells for CO_2 storage. Both technical and non-technical considerations are described. Key aspects of the report include a description of the data requirements for screening wells for their re-use potential, along with the technical requirements for ensuring well integrity and secure re-use. Existing wells may not be suitable for re-use in their current state, and may require intervention to ensure suitability for the desired CO_2 storage purpose. As a minimum requirement, wells will likely require workover and recompletion, with replacement of primary barrier elements. Irretrievable secondary barrier elements that cannot be replaced will require verification through logging and/or other integrity testing. A dedicated well screening software tool has been developed and applied to a portfolio of case studies to develop a knowledge-base to support decision-making for well re-use. Findings from the case study assessments provide an indication of the requirements for re-purposing existing wells for use in CO_2 storage operations. Non-technical aspects including policy and regulatory issues are also identified, while results from an experimental programme are summarised and used to inform possible directions for future research.

The recommendations outlined in this report have been developed to provide insights into the factors that need to be addressed when considering existing wells for re-use in CO_2 storage operations. The recommendations are intended to:

- Provide industry with recommended means for qualification and re-purposing of wells;
- Assist regulators in understanding the potential for re-using wells;
- Provide a foundational knowledge-base for well re-use, which can be used as initial recommendations for future guideline development;
- Identify future research requirements to assist the scientific community in addressing the outstanding uncertainties around well re-use potential.

A core aspect of the REX-CO_2 project was the development of the well re-use screening tool, which is underpinned by assessment criteria identified through rigorous review of well re-use projects, together with current standards and guidelines for ensuring well integrity. The project team draws from international experience from the Netherlands, France, UK, Romania and the USA, where the suitability and efficacy of the screening tool was tested across a range of case study sites. These included a combination of on- and offshore settings, depleted gas and oil fields, and saline aquifer sites. Recommendations developed during the project are primarily about enabling opportunities, taking advantage of existing well locations and infrastructure to accelerate deployment of CO_2 storage. The recommendations concern:

- High level screening of wells to determine if they may be of use in CO_2 storage projects;
- Detailed screening of existing well infrastructure to determine the degree to which it may be appropriate to re-use;
- Information, data and knowledge sharing to maximise well re-use opportunities;
- Directions for further experimental research to improve fundamental understanding of well integrity in the context of re-use for CO_2 storage.

A list of REX-CO_2 technical deliverables is available in Appendix A.

Contents

Tables

Figures

Glossary of key terms

Intervention	To conduct maintenance or repair operation on a well
Well completion	Series of procedures performed on a drilled and cased well to prepare it for production or injection
Recompletion	Replacement of existing completion and installation of new completion equipment (e.g. tubing, packer, wellhead components)
Remediation	Operation to correct issues with a well
Repurpose	Conversion of an existing well for future re-use
Re-use	The act of re-using a well
Workover	Any maintenance or remedial operation on the well following initial completion
Well Barrier Element (WBE)	One or several dependent components that prevent uncontrolled flow of fluids within or from the well. Primary barrier elements are in direct contact with the produced and/or injected fluids, whereas secondary WBEs serve as a backup in case of primary WBE failure
Well Barrier Envelope	A combination of one or more WBEs that together prevent uncontrolled flow of fluids within or from a well

1. General

1.1. Introduction

Oil and gas infrastructure that have reached the end of their commercial life for producing hydrocarbons are sometimes considered for re-purposing as part of new Carbon Capture and Storage (CCS) infrastructure networks. It is argued that re-purposing such assets could potentially reduce the upfront capital costs of deploying CCS technologies at large-scale (>100s million tons/year). Existing oil and gas fields provide a significant resource for geological storage of CO_2, while also benefitting from the following:

- Proven reservoir and top seal pairings;
- Free pore volume available following hydrocarbon production;
- Availability of site characterisation and operational data;
- Knowledge of field dynamics and behaviour based on prior operations;
- Availability of existing useable infrastructure where applicable.

With increasing numbers of oil and gas fields approaching the end of their productive lifetimes across the globe, there is an opportunity to convert existing facilities for re-use in CO_2 storage operations (DOE, 2017). Despite initiatives to re-use existing pipelines and other surface infrastructure, little attention has been given to the re-use potential of existing oil and gas wells to date. Well integrity and remediation studies have generally focused on legacy abandoned wells rather than operational wells that may have potential to be re-used (Carey, 2013; Wiese *et al*., 2019; Caroll *et al*., 2016., Sminchak *et al*., 2016). The need to facilitate timely deployment of CO_2 transport and storage infrastructure while reducing costs, has precipitated recent interest in re-purposing existing oil and gas infrastructure (BEIS, 2019; CAG, 2019).

Although few instances of re-using wells for CO_2 storage-related purposes have been documented, it is not an entirely new concept, and has been undertaken at several demonstration and pilot sites, including Lacq-Rousse in France (Prinet *et al*., 2013; Thibeau *et al*. 2013) and K12-B in the Netherlands (Vandeweijer *et al*., 2021). Extensive experience of re-purposing existing wells for use in CO_2-rich environments has also been developed over many decades at CO_2-Enhanced Oil Recovery operations in the United States (Bowser *et al*., 1989; Power *et al*., 1990; Folger and Guillot, 1996; Lamb *et al*., 2016). At least three proposed full-scale commercial projects dedicated to long-term storage have considered the possibility of re-using wells for CO_2 storage in the North Sea. Firstly, the Kingsnorth CCS Project conducted a re-use assessment of existing wells in the Hewett Gas Field. The option of re-use was eventually deemed unsuitable in this case because of a combination of factors, including the age of the existing well infrastructure, high level of uncertainty around the condition of well barriers, scarcity of key data, and additional uncertainty related to partial abandonment and sidetracks in some wells (E.ON, 2011). Conversely, detailed technical studies established that re-using existing production wells would be feasible for the Peterhead CCS project (Shell, 2015), also in the UK, and at Porthos in the Netherlands sector of the North Sea (Neele *et al*., 2019). The Peterhead project was cancelled in 2015 following withdrawal of financial support from central government. At the Porthos site, the intention remains to re-purpose the existing well infrastructure, with operation planned for 2024/2025. The projects above are summarised in REX-CO_2 Deliverable D2.1 (Opedal *et al*., 2020).

Several technical uncertainties and regulatory issues around the potential for re-using existing wells for CO_2 injection were identified by the ACT Acorn Project (ACT Acorn, 2019):

- Differences in basis of design for oil and gas wells relative to CO_2 injection wells;
- Sub-optimal bottom-hole location for CO_2 injection;
- Uncertainty around downhole condition of wellbore and potential need to acquire additional information;

- Potential requirement for remedial intervention, beyond standard workover to replace tubing and completion equipment;
- Potentially different risk profiles for re-purposed wells relative to new wells specifically designed for CO_2 storage;
- Potential for uncertainty around transfer of assets and decommissioning obligations due to unclear or imperfect regulatory requirements.

The REX-CO_2 project was initiated in response to the need to address the uncertainties concerning the potential role of re-using wells to expedite development of CO_2 storage. A key output of the project is a well screening process and an evaluation tool which can be used to perform preliminary assessment of the suitability of existing oil and gas wells for re-use in CO_2 storage operations. During development of the tool (further described in Section 1.5), a suite of technical requirements was identified, informed by applicable standards and guidelines for ensuring well integrity.

1.2. Objective

The REX-CO_2 project was initiated to address the lack of a dedicated well screening process specifically for re-using existing wells for CO_2 storage operations. The objective of this report is to provide recommendations for re-using existing wells for CO_2 storage, in compliance with the International Standard for Carbon dioxide capture, transportation and geological storage (ISO, 2017a). Findings from the REX-CO_2 project have been used to develop recommendations based on the technical requirements for re-using wells, and potential regulatory issues have been identified. Development of the recommendations also consider existing well integrity standards and guidelines for oil and gas wells, which have informed the development of the REX-CO_2 screening process and software tool.

The recommendations have been developed in order to provide insights into the factors that need to be addressed when considering existing wells for re-use in CO_2 storage operations. The recommendations will:

- Provide industry with recommendations for qualification and re-purposing of wells;
- Assist regulators in understanding the potential for re-using wells;
- Provide a foundational knowledge-base for well re-use, which can be used as initial recommendations for future guideline development;
- Identify future research requirements to assist the scientific community in addressing the outstanding uncertainties around well re-use potential.

1.3. Technical scope

While the scope of this report is limited to the suitability of the wellbore itself, it is important to note that the potential for re-using existing wells will also depend on linkages to surface infrastructure, including pipelines and well platforms (in the case of offshore operations), and to the subsurface storage reservoir and caprock system (Figure 1). If the well is not sufficiently connected to suitable surface and subsurface components of a CO_2 transport and storage network, it may not be technically feasible, nor economically viable to re-use a given well. Well status and accessibility will also be important to consider. The design lifetime of existing platforms may be particularly relevant to the feasibility of re-using offshore wells. It may be possible to extend the lifetime of a platform to enable re-use in a CO_2 storage project (Shell, 2015). Platforms will also need to be able to accommodate the topside facilities required for CO_2 injection, including connections to the transport infrastructure, and compressors for increasing the CO_2 stream pressure to the required injection pressure. Some considerations around the re-use of offshore platforms and subsea manifolds are discussed by Grimstad *et al*. (2019).

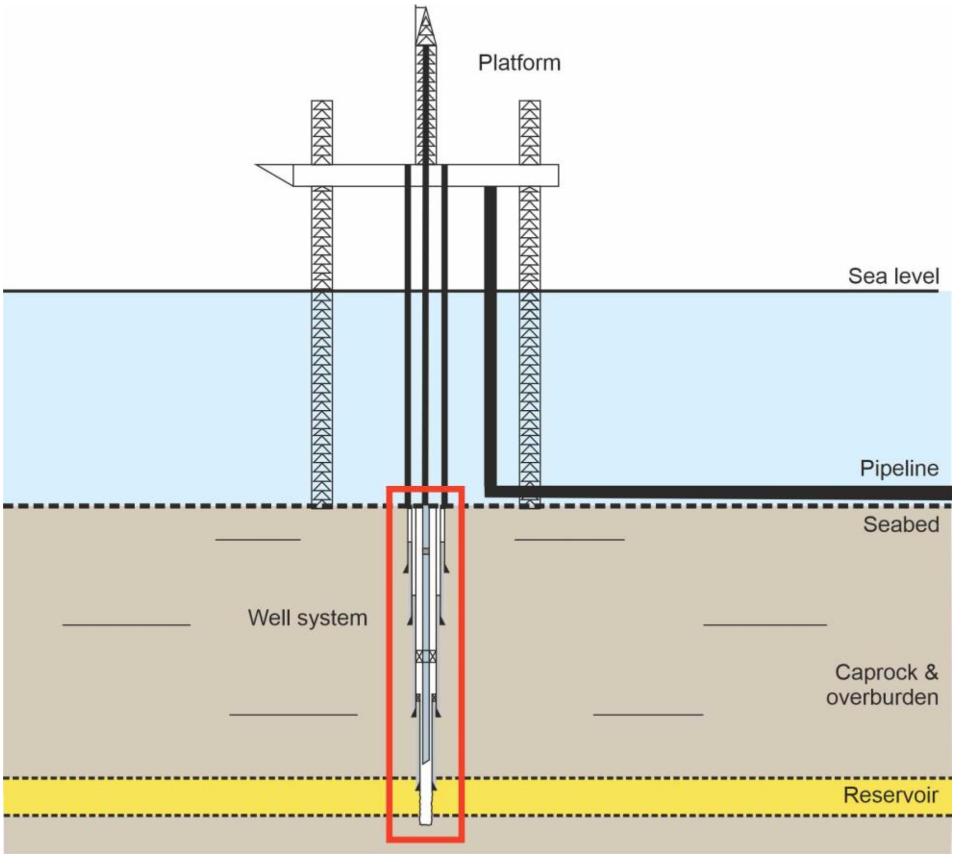


Figure 1. Schematic of wellbore with connections to other parts of the CO_2 transport and storage system. Scope of report is indicated by the red rectangle. Diagram provides a representation only, is not intended to illustrate any specific development concept, and is not to scale.

The scope of the recommendations concerns the following:

- Re-use of existing oil and gas wells designed for primary purposes other than CO_2 injection and storage;
- Re-use qualification in terms of structural integrity and zonal isolation of existing wells;
- Practical considerations of the potential to re-use wells;
- Re-use of existing wells for any CO_2 storage purpose, including injection, monitoring and pressure relief;
- Approaches to remediate wells such that they can be safely re-used for CO_2 storage purposes;
- Non-technical aspects such as policy and regulatory environments;
- Future research requirements.

1.4. Application

The life cycle of a CO_2 storage project commences with site screening and selection, following which, selected candidate sites are extensively characterised prior to project design and development (Figure 2). This report primarily concerns the site screening and selection phase of candidate CO_2 storage projects, where potential wells would be identified and assessed against the criteria for re-use. The recommendations are also relevant to both the site characterisation, and the design and development phases.

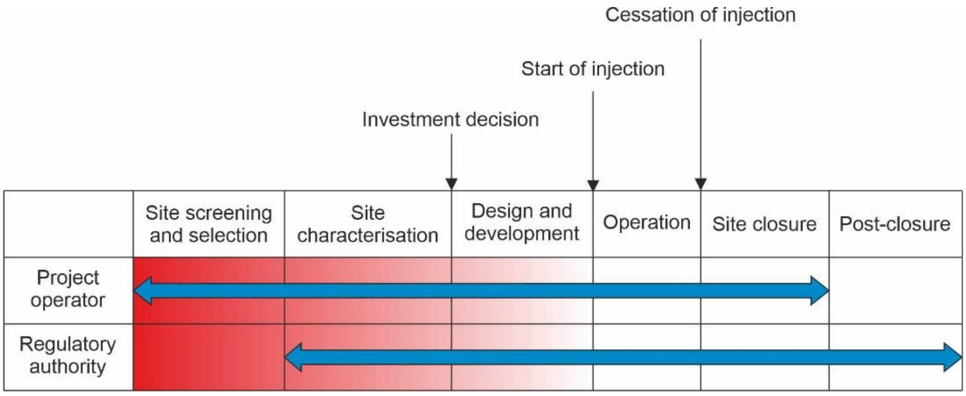


Figure 2. Life cycle diagram for CO_2 storage projects based on periods outlined in ISO (2017a). The project phases within the scope of this report is shown by the shaded red region.

In Europe, the storage complex as defined in the CCS Directive (EC, 2009), is central to the screening and characterisation of storage sites. The storage complex includes *"a defined volume area within a geological formation used for the geological storage of CO_2 and associated surface and injection facilities, and surrounding geological domain which can have an effect on overall storage integrity and security; that is, secondary containment formations."* This composite of geological reservoirs, and geological and engineered barriers, provides the long-term accommodation space and containment of CO_2 in the deep subsurface. Evidently, the re-used or newly built well with its barrier elements forms an integral component part of the storage complex, which will require detailed screening, characterisation and ongoing risk management. Secure and effective isolation is required throughout the development, operational, and post-closure periods.

Potential oil and gas fields or other sites selected for CO_2 storage are identified following a rigorous site selection and characterisation process. Such activities include an assessment of the suitability and integrity of the intended storage reservoir, storage capacity and injectivity estimation, and assessment of risks to containment. The expected performance of the site will be assessed against a set or subset of geological (storage capacity, integrity and injectivity), technical, economic and geographic criteria. For sites with history of previous oil and gas exploration and production, the potential re-use of existing infrastructure such as pipelines, platforms and wells, may be attractive for techno-economic reasons. Existing wells may potentially be re-used for injecting CO_2, monitoring reservoir dynamics, or for producing in-situ brine to relieve excess reservoir pressure. In many cases, wells are likely to be suspended or temporarily plugged prior to being re-purposed. The recommendations in this report are equally applicable to both active and suspended wells that might be considered for potential re-use.

There are various ways in which existing wells could be prepared for re-use:

- Re-use without modification;
- Workover with modification;
- Side-track from a portion of the well;
- Deepening the wellbore to access a deeper target;
- Milling or perforating to access a shallower target;
- Partial plugging of well sections;
- Re-entry of an abandoned well.

In most cases, a degree of modification will be required in order to re-use a well for CO_2 storage. Re-use of a well in its existing state without workover or re-completion will not usually be appropriate unless the original well functional specifications and basis of design are compatible with CO_2 storage requirements, and well integrity can be verified and successfully monitored. It may also be technically and commercially challenging to re-use abandoned wells, particularly in offshore settings. Significant costs may arise from re-entering abandoned wells and there will be significant uncertainty associated with the condition of the well including downhole materials. Despite these challenges, these options may be applicable and economic compared to drilling new wells in certain settings.

Once a site has been identified as a suitable candidate for CO_2 storage, any potential for re-use of existing wells must be considered in a full-field context and within an overall transport and storage system. One aspect of particular concern is that current wells may not be suitably located within the intended storage site, which may compromise the case for re-use.

It is recommended to conduct reservoir simulation studies to evaluate the position of wells with respect to the intended CO_2 storage operation. Modelling studies should consider the location of wells with respect to storage complex boundaries and the impact of well location on anticipated CO_2 plume migration, also accounting for the injection scheme. It is also important to consider the spatial relationship with other wells, including abandoned wells, subsurface structures and surface facilities. Re-use of an existing well for CO_2 injection might be precluded if it is located close to a feature that could compromise the performance of a CO_2 storage project, such as a poorly-abandoned legacy well or critically-stressed fault. Conversely, re-use of a well might be considered for monitoring migration of CO_2 towards such features. Should existing wells not be optimally located, it may be practical to consider sidetracking the wells to access optimal locations within the reservoir while abandoning the main borehole following best practice procedures to ensure well integrity.

Studies should also provide anticipated well functional specifications including mechanical and temperature load profiles and chemical characteristics of the injectate, which are required to assess the suitability of wells for re-use.

Well diameter is also an important consideration for re-purposing existing wells. The diameter will need to be sufficient to accommodate tubing and completion equipment suitable to provide the required injectivity. The diameter at a specific interval may also constrain the potential to use certain monitoring equipment.

1.5. The REX-CO_2 screening tool

A key output of the REX-CO_2 project is an assessment framework and a software tool to aid the process of qualitatively screening wells for their potential suitability for re-use in CO_2 storage operations. The REX-CO_2 project screening tool will be made publicly available as a stand-alone executable downloadable from the REX-CO_2 website following project completion (https://www.rex-co2.eu/).

The assessment framework methodology follows multiple decision trees through a series of queries relating to the suitability and condition of the wells and their components under assessment. The tool addresses five key categories:

- Structural integrity;
- Primary well barrier integrity;
- Secondary well barrier integrity;
- Material compatibility;
- Risk of out of zone injection.

The tool and its underlying methodology are described in the REX-CO_2 Deliverable Reports D2.2 (Pawar and van der Valk, 2020), D2.3 (Pawar *et al.*, 2021) and D2.4 (Brunner and Pawar, 2021). The technical requirements described in Section 3 have been used to determine the critical requirements that have been incorporated into the REX-CO_2 screening process. Results are expressed as a colour-coded grading for each of the five key categories, providing an indication of the degree of remedial intervention required to convert the well (Table 1). The screening tool interface is illustrated in Figure 3.

Table 1. Colour-coding used for easy interpretation of results produced by the REX-CO_2 well re-use screening tool.

	Explanation
(green)	No or only minor remediation could be expected for the well in its current state.
(yellow)	Moderate remediation or additional verification efforts could be expected, and a hazard identification and risk management strategy could be prepared for the well in its current state. One may expect remediations that do not require a workover rig, e.g. wireline or coiled tubing interventions.
(grey)	Critical information is missing for assessment with the screening tool. It is advised to look for additional data, acquire additional data (e.g. by running logs) or look for offset data, and then reassess the well with the screening tool.
(orange)	Severe remediation and a comprehensive hazard identification and risk management strategy on retrievable/replaceable items could be expected. One may expect remediation work that requires a rig or workover unit, e.g. to recomplete the well or abandon obsolete sidetracks.
(red)	Severe remediation and a comprehensive hazard identification and risk management strategy on non-retrievable/replaceable items could be expected, based on the screening. One may expect remediation work on annular cement or cemented casings; e.g. cement repairs or other technically challenging operations with highly uncertain outcomes.

It is recommended that the REX-CO_2 screening tool is used to assess the suitability of existing wells located at sites identified as having potential for CO_2 storage. Application of the tool is most appropriate during the screening phase of a CO_2 storage project, where it can provide an independent and consistent step-by-step guide through the well screening process. The tool is optimised to identify red flags or potential show-stoppers, and therefore provides an efficient means of identifying and excluding problematic wells while also identifying those warranting further engineering assessment for re-use purposes.

It should be noted that the tool does not provide specific workflows for screening wells for purposes other than re-use for CO_2 injection. However, it can be applied to screen wells for other purposes such as monitoring at CO_2 storage sites. While the same criteria are likely to be required in such cases, it may not always be necessary to screen certain aspects, such as the material compatibility in relation to CO_2-rich fluids and temperature perturbations. For example, dedicated monitoring wells located away from injection wells may not be subjected to significant temperature changes, nor necessarily exposed to CO_2-rich fluids.

A substantive working-knowledge of wells and well engineering is a prerequisite for effectively using the tool, however the tool is not intended, and is not suitable for substituting for a full engineering assessment during project design. The tool supports identification of particular well elements that require further attention and detailed evaluation by requisite experts.

In practice, the tool should be used as part of a holistic site characterisation process, considering the wider context of the field/site. The usefulness of the REX-CO_2 screening results is highly data dependent, as addressed in Section 2.

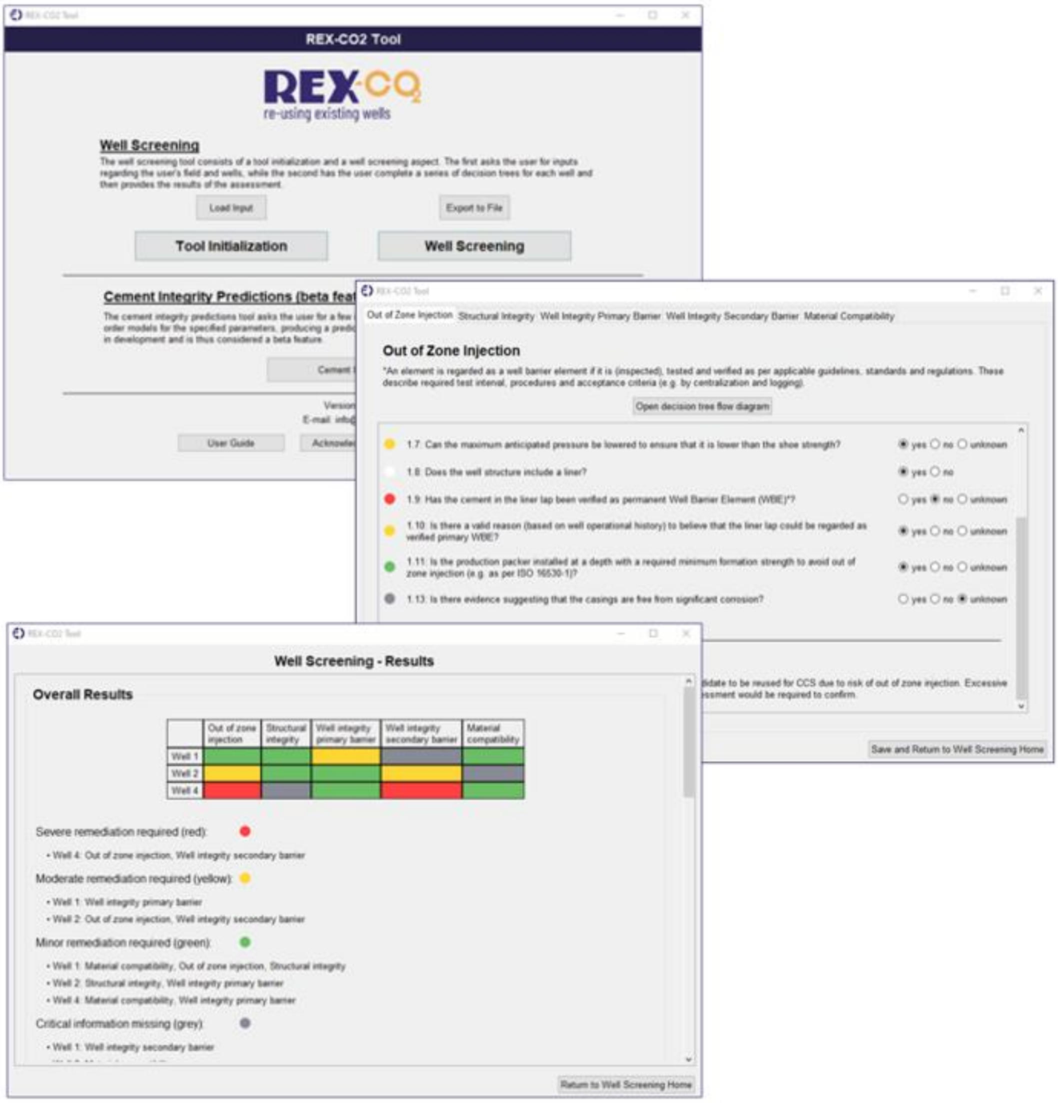


Figure 3. Screenshots illustrating the REX-CO_2 screening tool interface. Top: Initial dashboard screen, Middle: Example well screening page (for the Out of zone injection category), Bottom: Example results screen, showing results for three wells.

2. Data compilation and acquisition

2.1. Data requirements for screening

Assessment of the potential to re-use existing wells should be undertaken on a case-by-case basis. Recommended data for undertaking an initial assessment of the potential for re-using a well are included in Table 2. Lack of data availability can prohibit a full assessment of the potential for re-using a well.

Table 2. Data required to facilitate accurate assessment of well suitability for re-use in CO_2 storage operations.

Category	Data	Description
Reservoir and caprock	Target formation	Depth, thickness, lithology, mineralogy, hydraulic properties and rock mechanical properties required to establish suitability for CO_2 injection or other CO_2 storage site purpose. Reservoir characteristics at the completion interval are particularly important.
	Caprock	Depth, thickness, lithology, mineralogy, hydraulic properties and strength required to establish efficacy as a caprock. Secondary caprocks may be required as secondary well barrier components.
	Pressure and temperature, including expected conditions during CO_2 injection and storage	Pressure and temperature are critical to understanding the phase behaviour of CO_2, injectivity, and mechanical constraints. The anticipated pressure and temperature response should be predicted using reservoir simulation or other suitable techniques.
	In-situ fluid composition	Composition of reservoir fluids are important in the context of material selection for CO_2 storage wells.
	Production history of the well including reservoir and caprock response to the hydrocarbon production phase	Knowledge of the production/injection history is critical to understanding the load history of the reservoir, caprock and well system.
Well construction and history	Drilling history and completion	Drilling and completion history required to assess the operational lifetime of well components with respect to anticipated loads.
	Well design and configuration	Design and configuration is required to establish the position of well components and completions, structural integrity, well barrier placement and out of zone injection risk, and suitability for re-use.
	Workover history	Post-completion well interventions and workovers.
	Side-tracks	Position of any side-tracks. Side-tracks may preclude re-use of parent wells, and may require special considerations for re-use.
	Cement composition	Chemical and strength characteristics of cement for analysis of compatibility of cement for anticipated CO_2 storage operations.
	Cement evaluation logs	Indications of issues with original cement jobs, and identification of any defects identified by any subsequent cement evaluation operations.

		Verification of well barrier elements (WBEs) if recently logged.
Well integrity record	Well barrier schematics	Establishment of well barriers and barrier elements for well integrity assessments.
	Abandonment plan (if applicable)	Applicable for abandoned wells. Placement of abandonment plugs, verification of abandonment barriers, current status of well, wellhead accessibility/well access constraints.
	Completion reports or End of well report	Includes numerous data including daily drilling reports, well schematics, deviation data, geological descriptions, pressure measurements and more.
	Mechanical integrity test	Data to verify the mechanical integrity of well components.
	Corrosion logs/tests	Data to verify corrosion status of cased well sections.
	Formation integrity/leak-off test	Mechanical integrity of the reservoir/caprock/overburden and fracture pressure estimates. Data compiled from offset wells commonly used in absence of test data from individual target wells.
	Annular pressure	Annular pressure monitoring data is used to verify well integrity.
	History of well performance and issues	Examples may include mud-losses, annular pressures or injectivity.
	Well maintenance history	Post-completion well interventions and workovers, well integrity monitoring records.
	Load history	Lifetime loads to which the well has been subjected, including loads associated with production/injection history, structural loads such as Vortex vibrations, (Metocean) fatigue loading etc.

2.2. Data availability and knowledge transfer

The availability of data differs across the countries represented within the REX-CO_2 project consortium, however open data repositories available in some jurisdictions contain much of the well construction and completion information for released wells (See Box 1 for example from the UK).

Ideally, information required to undertake full detailed screening assessments would be made available to enable consideration of well re-use in CO_2 storage projects.

For prospective CO_2 storage site operators aiming to transition a field from hydrocarbon production to CO_2 storage, close collaboration with current field operators is essential in order to fully assess re-use feasibility, as many of the data required is generally unavailable in public domain repositories. Examples of such data include corrosion status, well barrier integrity tests, annulus pressure history and details of previous workover/remediation activities. Assessment of packers, downhole safety valves, wellhead and Christmas (X-mas) tree components also requires knowledge of the most recent inspection and maintenance testing, which are not usually openly available.

Early access to such data prior to cessation of production would facilitate timely well re-use assessments. This may potentially avoid situations whereby opportunities to re-use promising well candidates are lost should the wells be permanently plugged and abandoned.

It is recommended that prospective wells located in promising potential storage locations should be identified early in order to facilitate discussion of potential well re-use between hydrocarbon operators, regulatory authorities and prospective CO_2 storage site operators. Data sharing and transfer would form a key element of such discussions.

Data availability should also be considered when sanctioning new oil and gas well operations at promising CO_2 storage candidate sites. Documenting full well history and barrier status for all new well developments would greatly enhance the ability of future CO_2 storage operators to make effective assessments of well re-use potential and to aid in decision making.

Box 1: UK National Data Repository

The United Kingdom's National Data Repository (NDR) is a key element of the UK's digital infrastructure, providing access to petroleum-related information and samples. The scope of the NDR encompasses both the information that is generated and the samples that are acquired during activities related to offshore exploration and production licences. Data can be accessed via the online NDR portal available at https://ndr.nstauthority.co.uk/.

The data commonly held for wells include all stages of the lifecycle of a well, from pre-drill through drilling operations, data collection and interpretation, well testing and abandonment operations. Well reports and logs comprise a significant proportion of the available information. Guidance on the data reporting obligations for licence holders is provided at https://www.nstauthority.co.uk/data-centre/national-data-repository-ndr/.

Whilst initial well construction and completion reports and logs are usually available for the vast majority of wells, there are some issues with lack of machine-readable data for some older wells. In some cases, this lack of information may preclude the potential for re-use altogether, but lack of basic well construction data is only likely to be an issue for older legacy wells that may have already been permanently plugged and abandoned in any case.

However, some of the data required to evaluate well re-use is not readily available. Examples include annular pressure history, and maintenance and well barrier verification records. While this can be problematic for screening wells for their re-use potential in some cases, it may not be considered as critical if the tubing, packer and other primary barrier elements need to be replaced with new components compatible for the operating conditions anticipated during CO_2 storage.

Numerous other jurisdictions also maintain open data repositories containing data and reports associated with released oil and gas exploration and production wells. A non-exhaustive list of other examples are given below:

Norway: https://www.npd.no/en/diskos/,
The Netherlands: https://www.nlog.nl/en/boreholes,
USA (State of Louisiana): http://www.dnr.louisiana.gov/index.cfm/iframe/340,
USA (Texas): https://www.rrc.texas.gov/oil-and-gas/research-and-statistics/obtaining-commission-records/oil-and-gas-well-records/

3. Technical requirements for screening

Ensuring that injected CO_2 remains in the target reservoir during operations has important operational, health and safety, environmental, regulatory, economic and social licence implications. Understanding the design and functional requirements for CO_2 storage wells is key to assessing the suitability of an existing oil and gas well for re-use in a CO_2 storage operation. Prior to the REX-CO_2 project, there was no assessment framework or process available in the public domain to aid the evaluation of wells for their potential suitability for re-use in CO_2 storage applications. The standards and guidelines highlighted in Table 3 have formed the basis for determining the critical technical requirements for re-using existing wells. These technical requirements form the criteria used in the REX-CO_2 screening tool described in Section 1.5. At present, there is only a single International Standard specifically designed for CO_2 storage wells, but there are multiple standards and guidelines related to oil and gas wells. The principles of these are transferrable subject to a robust understanding of the conditions expected to be encountered in a given CO_2 storage project.

Table 3. Key standards and guidelines relevant to assessment of existing wells for CO_2 storage operations.

Document	Description	Reference
International Standard ISO 27914:2017	Developed for CO_2 capture, transport and geologic storage, and currently provides the only design standards specifically for CO_2 storage wells	ISO, 2017a
US Environmental Protection Agency's (US-EPA) Underground Injection Control (UIC) programme Class-VI well construction guidance	Identifies the requirements for constructing CO_2 storage wells	EPA, 2012
International Standard ISO 16530-1	Standards for oil and gas well construction and integrity	ISO, 2017b
NORSOK D010:2021	Standards for oil and gas well construction and integrity	Standards Norway, 2021
Oil and Gas UK, Well Life Cycle Integrity Guideline, Issue-4, 2019.	Well life cycle integrity guidelines	OGUK, 2019

The primary objective of the above standards and guidelines is to ensure that wells are constructed such that they maintain integrity during their lifetime under the anticipated conditions to which they are subjected. All of these standards and guidelines recommend the presence of multiple well barrier envelopes to ensure that injected CO_2 and in-situ fluids are contained, preventing unintended and uncontrolled flow of fluids within or out of a well to the external environment.

A well barrier envelope is a combination of one or several well barrier elements (WBEs). The objectives of a well barrier are to:

- Withstand the maximum anticipated combined loads to which it can be subjected;
- Function, as intended, under the expected pressure, temperature, chemical (CO_2- rich, hydrocarbon-rich, high-salinity, trace amounts of other corrosive constituents, hydrogen etc.) and mechanical stress conditions through the entire life cycle;
- Prevent uncontrolled and unintended flow of injected CO_2 and in-situ fluids (hydrocarbons and/or brine) within the wellbore or to/from the external environment.

In the ISO and NORSOK standards, two independent barrier envelopes are recommended at all times as a minimum requirement; a primary and secondary barrier envelope (Figure 4). In certain cases, more than two barriers could be required or present. The primary barrier envelope is the first barrier and is in direct contact with reservoir fluids at reservoir pressures. The secondary barrier envelope is not directly exposed to fluids or pressures and provides back-up in the event of primary barrier failure. It provides the secondary line of defence against unintended, uncontrolled fluid flow from the wellbore to the external environment. The two barrier envelopes differ mainly through the combination of WBEs of which each barrier is comprised.

The primary well barrier envelope commonly comprises a combination of the following barrier elements:

- Caprock;
- Production (long-string) casing/liner cement;
- Production (long-string) casing/liner (can alternatively form part of the secondary barrier envelope depending on location of liner hanger with respect to the packer);
- Production packer;
- Liner hanger/packer;
- Tubing;
- Downhole/sub-surface safety valve (SSSV).

The secondary well barrier envelope is commonly composed of a combination of the following barrier elements:

- Impermeable formation;
- Casing cement;
- Casing with hanger and seal assembly;
- Wellhead with valves;
- Tubing hanger with seals;
- X-mas tree and tree valves, connections.

The following recommendations are structured to align with the five decision tree categories incorporated into the REX-CO_2 screening tool (Section 1.5).

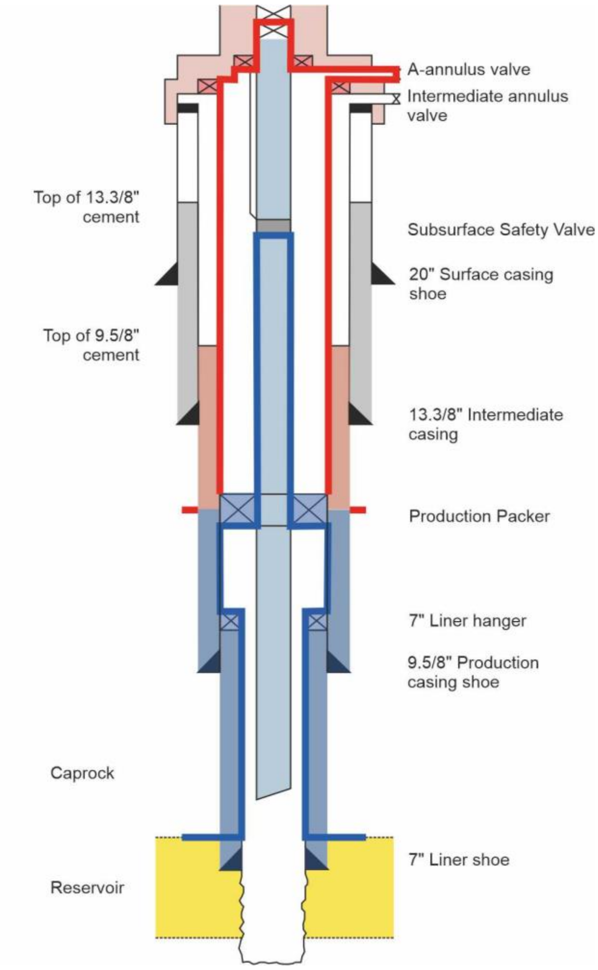


Figure 4. An example wellbore barrier schematic based on ISO-16530 (ISO, 2017b). The primary barrier envelope is indicated by blue lines & secondary barrier envelope is indicated by red lines.

3.1. Structural integrity

A combination of the wellhead, conductor casing and/or surface casing strings provide structural integrity to a well. Structural failure may adversely affect the well pressure containment boundary (OGUK, 2019). It is anticipated that it will be highly challenging, if not impossible to remediate the components that provide the structural integrity to the well in the event of observed structural damage through:

- Internal and/or external corrosion;
- Lateral loading such as from squeezing formations or earthquakes;
- Degradation of the formation that supports the load-bearing casing due to cyclic, climatic and/or thermal loads;
- Vortex vibrations, (Metocean) fatigue loading, lifetime loads.

The predicted consumed life of the structural integrity components should be assessed along with the anticipated lifetime load profile associated with the CO_2 storage project. The remaining functional life of the combination of structural components should be suitable for the anticipated project. Remedial work would be required should any of the structural integrity components lack the required functional life. For offshore wells, structural surveys are highly technical and expensive operations, involving combinations of diver activities and remote operating vehicles. Structural integrity should therefore be assessed as much as possible through desk-study with minimal capital expenditure. For the structural conductor in offshore wells, the following assessments are recommended during initial desk-based screening:

- Thickness of conductor pipe (or thickness across the splash zone);
- Cementation of surface casing to surface (or above the splash zone);
- Year of construction and years of service;
- Presence/availability of scheduled maintenance and/or inspection reports;
- Connection to a cathodic protection system.

If remedial action is not possible then it is unlikely that the well would be considered as a suitable candidate for re-use in CO_2 storage operations.

3.2. Primary barrier envelope integrity

The primary barrier envelope includes all elements in direct contact with the produced/injected fluid. Elements regarded as primary barrier elements should be inspected, tested and verified as per applicable guidelines, standards and regulations that describe test intervals, procedures and acceptance criteria. If present, the integrity of the following elements should be verified:

- SubSurface Safety Valve (SSSV) and production tubing below SSSV if present and considered to form part of the primary well barrier envelope;
- Additional completion jewellery such as Sliding Side Door (SSD) or Side Pocket Mandrels (SPM);
- Production packers;
- Casing/liner strings across the caprock interval;
- Production casing or liner including liner hanger below production packer.

If no production packer is present, the well should be assessed to ascertain if the design allows for two independent barrier envelopes without a packer. If so, the responsible element(s) should be verified as barrier elements.

If present, any liner string penetrating the caprock should have been cemented across the caprock(s) interval.

A well may require remediation if any of the criteria above are not met.

3.3. Secondary barrier envelope integrity

The secondary barrier envelope includes all barrier elements which will be in direct contact with the produced/injected fluid in case of failure of the primary barrier. Elements regarded as secondary barrier elements should be inspected, tested and verified as per applicable guidelines, standards and regulations that describe test intervals, procedures and acceptance criteria. The integrity of the following elements should be verified:

- X-mas tree body and valves;
- Wellhead;
- Wellhead connections, seals and annuli valves;
- Combination of production casing and if present, liner including liner hanger;
- Cement at the relevant intervals.

A well may require remediation in the following circumstances:

- The combination of production casing and if present, liner, have not been cemented according to current national regulations and requirements;

- Sustained annulus pressures have been identified in any relevant annuli, or any other indication of cement integrity issues identified, including if reservoir fluids have been found while bleeding down the annulus pressure;
- Any other indications of integrity issues with the secondary barrier envelope.

It is recommended that the secondary barrier envelope includes an additional impermeable formation with no indication of integrity issues.

3.4. Material compatibility

3.4.1. Steel and elastomers

CO_2 storage wells contain materials that are, or may potentially be directly exposed to the CO_2 stream. Well components are therefore required to be composed of materials that can withstand harsh conditions, including pressure and temperature changes, and chemical effects related to the composition of brine and injected CO_2. The materials need to be compatible with the new load environments and corrosive fluid streams. The following conditions are recommended in order to positively identify a suitable candidate for well re-use:

In relation to acidity of CO_2 loaded fluids:

- Well materials exposed to the CO_2 stream and reservoir fluids should be composed of CO_2-corrosion resistant alloys. Table 4 provides recommended steel grades for different impurities that may be present in the CO_2 stream;
- Well designed to provide sufficient protection against galvanic corrosion;
- All sealing elements should be compatible with the anticipated high-CO_2-containing chemical environment. Replacement of the relevant items should be possible without a full workover;

In relation to temperature effects:

- Steel grade should be suitable for anticipated temperatures if temperature in the well is expected to exceed 150˚C (302 ˚F);
- All parts affected by low temperatures (for example by subjection to arctic conditions or through Joule Thomson cooling) should be rated for the anticipated conditions;
- The packer and completion operating envelopes should be suitable for the new load profile (for example during low temperatures at start-up of injection).

Should any of the WBEs fail to meet the criteria above, a workover or other mitigation action would be required in order to re-use the well.

The principal material compatibility challenges relate to impurities present in the CO_2 stream and the intermittency of operations. These intermittencies will increase risk of depressurisation and associated falls in temperature due to Joule-Thomson effects. Materials therefore require resistance to low temperature when the steel may become brittle.

Table 4. Indicative steel grades for different impurities that may be present in CO_2 streams or reservoir fluids. The application domain for each material will depend on several factors (including pH, temperature, chloride concentration etc.) which will need to be considered with respect to the specific operating environment. The materials are therefore provided as a general guideline. Given values are based on MR 0175/ISO 14156 (ISO, 2003) selection rules and internal Vallourec database (as detailed in REX-CO_2 Deliverable Report D3.6, Millet et al., 2022).

Impurities (concentration: recommended steel grade)		
H_2S (within the CO_2 stream or reservoir fluids)	**O_2**	**SO_2, NO_2, CO…**
<0.1 bar (1.5 psi): 13Cr or S13Cr <0.4 bar (6 psi): Super Duplex >0.4 bar (6 psi), no S: 28Cr >0.4 bar (6 psi), S: Ni based	Trace: S13Cr or Super Duplex	Ongoing research required

3.4.2. Cement

Carbonic acid is formed when CO_2 dissolves in water, and can chemically react with many commonly-used wellbore materials such as casing or cement (Yan *et al*., 2012; Ernens *et al*., 2018). Alteration of the composition of Portland cement can occur when calcium hydroxide reacts with CO_2 to form calcium carbonate, a process known as carbonation. This may not necessarily be a detrimental process because the cement becomes less porous and less permeable as a result. The reactivity of this system could also be mitigated by injecting dry CO_2, however this can result in drying and cracking effects which need to be carefully considered. Conversely, calcium carbonate dissolution into a CO_2-rich brine (i.e. low pH water) may result in increasing porosity and permeability and degradation of cement barrier elements (Carroll *et al*., 2016; Kutchko *et al*., 2007; Zhang and Bachu, 2011). The observations above are primarily based on laboratory experiments, whereas Carey *et al*. (2007) have shown that Portland cement from an old well in the SACROC CO_2-EOR field maintained its integrity in-spite of evidence of reaction with CO_2. These contradictory observations highlight the requirement for more controlled tests such as those outlined by Manceau *et al*. (2015), to be conducted at relevant and systematic conditions. It is possible that many of the laboratory experiments might have been performed at conditions that do not reflect in situ conditions, and potentially exaggerate the severity of the chemical interactions. Acquiring more accurate knowledge of the composition of fluids in contact with primary barrier cemented zones at relevant subsurface conditions would be of significant value. If such an opportunity could be identified, providing an international research consortium with access to a demonstration well would be of great benefit in understanding the behaviour of exposed cement in-situ. Depending on the original design and selected materials, many older wells might require significant workovers in order to ensure integrity as CO_2 storage wells. The industry has also developed CO_2-resistant cement compositions designed to withstand CO_2-rich conditions.

REX-CO_2 Deliverable D2.1 (Opedal *et al*., 2020) reviewed large-scale assessments of re-use, finding differences in the attitudes of industry-led CCS projects in relation to the suitability of Portland Cement in CO_2 storage environments. The Kingsnorth CCS Project highlighted the need for a CO_2-resistant cement, and recommended the development and testing of non-Portland cement systems (E.ON, 2011). In contrast, the Peterhead and Rousse CCS projects concluded that the existing Portland cement systems would not preclude the re-purposing of the existing wells for CO_2 injection (Shell, 2015; TOTAL, 2015).

The contrast in conclusions regarding the integrity of Portland cement in re-purposed wells highlights the need for more systematic research at relevant conditions to assess the actual suitability of Portland Cement systems in CO_2 storage environments. Given that different operators may have contrasting views on the required composition of wellbore cements in CO_2 storage wells, the REX-CO_2 screening tool focuses on the quality of cement at relevant well barrier depths rather than cement composition.

3.5. Out of zone injection risk

Out-of-Zone Injection is a specific risk which can involve the injected fluid breaching to formations other than the intended injection zone, or to the surface or seafloor.

The well under consideration should be assessed such that potential risks of migration of injected fluid out of the target zone via the well/near-well zone will be identified. There can be multiple potential pathways for out-of-zone fluid migration. The risks should be identified based on estimated pressures, temperatures, presence and adequacy of cement barriers, status and strength of casing shoes and liner laps, etc. Additionally, information from cement evaluation logs (if any are available) and well history should be used during this assessment. The following recommendations would provide confidence that sufficient barriers are present to minimise the risk of out-of-zone injection should an existing well be re-used for CO_2 injection:

- Well reports should be interrogated to determine if the use of cement and quality of the cement job during construction of the well were sufficient to effectively isolate the injection zone. The aim should be to determine that casing and casing shoes were installed properly with adequate cement coverage over the appropriate depth intervals, and that the casing was centralised effectively to ensure effective cement placement around the full circumference of the well. If well records do not indicate use of centralizers during the cement job, or if sufficient records are unavailable, the well may still be considered for re-use if there are no indications of cement integrity issues. In some cases, it may be necessary to seek evidence to validate the effectiveness of the cements as a barrier;
- Cement evaluation logs should indicate effective cement bonding and qualify the cement as a barrier element at critical depths. If the aim is to re-use the well without replacing the existing production tubing, it may be challenging to acquire new logs. In this case, initial cement evaluation logs combined with other available indications (for example absence of sustained annular pressures) should provide confidence in the quality of the cement bond. Since re-completion is usually required, workover activities such as replacement of the existing completion string may provide an opportunity to acquire up-to-date cement (and casing quality) evaluation logs;
- The formation and casing shoe should have been tested by either a Leak-Off Test (LOT) or Formation Integrity Test (FIT), and the measurement result should be higher than the maximum anticipated pressure that the shoe would experience at that depth (e.g. maximum reservoir pressure minus hydrostatic head). Absence of such a test does not preclude the re-use of the well, however there must be confidence that the estimated fracture gradient around the casing shoe is greater than the anticipated pressure at casing shoe depth and that the cement job and cementation of the shoe was successful;
- If a liner with appropriate metallurgy is present and is not to be replaced during workover, the cement in the liner lap should have been verified as a permanent WBE by logging, centralising and pressure testing prior to installation of the liner top packer. If there is insufficient evidence for this, then it is recommended that there should be a valid reason (based on operational history) to believe that the liner lap has been verified as a WBE;

- The formation strength at the depth at which any packers have been installed should possess formation strength sufficient to avoid out of zone injection, as detailed in ISO 16530-1. If not, then it is recommended to replace the packer or to install a new packer at a depth with the required minimum formation strength;
- Casings (and liner if present) should be free from significant corrosion. If evidence indicates to the contrary or is lacking, the suitability of the well for re-use should be considered uncertain and remediation efforts (e.g. workover) may be required.

If a workover is required in order to re-use a well for CO_2 storage, assessments should be undertaken to verify the new or remediated WBE performance. Workover activities also provide a potential opportunity to verify the presence and performance of pre-existing WBEs.

In addition to the quality of wellbore materials such as casing and cement, out of zone injection risk is influenced by the properties of the surrounding geological strata. Examples of data types required to characterise out of zone injection risk include:

- Cement evaluation logs such as cement bond logs;
- Casing evaluation logs;
- FITs, LOTs, minifracs or extended leak off tests;
- Wireline geophysical logs (sonic logs, image logs etc.);
- Subsurface fault distributions, maps and sections;
- Masterlogs and lithology logs;
- Mineralogical data for characterisation of clay content etc.

4. REX-CO_2 case studies and recommendations

To date, there are few documented cases where existing wells have been considered for re-use in CO_2 storage operations (Opedal *et al*., 2020). To develop an understanding of the issues likely to be encountered, the technical criteria outlined in Section 3 have been used as the basis for a screening exercise applied to several case study sites. The resulting observations provide a knowledge-base with which to identify key issues which should be addressed through detailed well by well assessment. The observations have been used to identify implications for redesign and recompletion of wells, and to formulate recommendations for verifying well integrity status. In practice, detailed assessments should be undertaken on a well by well basis to identify the requirements for safely re-purposing existing wells, however the following observations provide a generalised indication of the potential activities that may be required.

4.1. Case study assessments

To highlight the implications for verification, design and recompletion requirements, the REX-CO_2 screening tool has been applied to eight published case studies. The case studies represent a range of on- and offshore settings, including depleted gas field settings, oil fields and saline aquifers. The diverse characteristics of the case studies are summarised in Table 5, and demonstrate that the tool can be used to evaluate a wide variation of well configurations and scenarios. Two of the case studies, the P18-2 and Rousse fields, provide an opportunity to compare the results of the screening approach against engineering assessments conducted by independent experts for purposes of re-using wells in industrial CO_2 storage projects (Zikovic and van der Valk, 2021; Guy and Cangemi, 2022). The Rousse case study is the only case in which it was possible to validate the performance of the tool against an operational CO_2 storage project where a well has been successfully re-used. In both cases the outputs from the REX-CO_2 tool closely resembled those of the independent expert assessment. Box 2 provides a brief comparison between the REX-CO_2 screening tool results and the well re-use assessment conducted for the P18-2 field as part of the Porthos CO_2 storage project.

The consistent screening approach facilitated by the REX-CO_2 tool enabled a simple and fair comparison between wells. In this section, the case study learnings are summarised and used to inform the development of recommendations for converting existing wells for CO_2 storage operation.

Table 5. Summary of REX-CO_2 case studies and key references.

Case study name	Country	Onshore/offshore	Type	Reference document
P18-2 (Porthos)	Netherlands	Offshore	Depleted gas field	Zikovic and van der Valk (2021)
AB-field	Netherlands	Offshore	Depleted gas field	Rosener (2022)
Vaccum	USA	Onshore	CO_2-EOR field	Chen (2021)
Gullfaks Sør and Visund	Norway	Offshore	Oil fields	Grimstad *et al*., (2022)
Bunter Sandstone Closure 36	UK	Offshore	Saline aquifer	Williams and Hoskin (2021)
Hamilton	UK	Offshore	Depleted gas field	Williams and Hoskin (2022)
Rousse	France	Onshore	Depleted gas field and pilot CO_2 storage site	Guy and Cangemi (2022)
Salonta	Romania	Onshore	Depleted gas field (abandoned)	Dudu (2022)

Box 2: P18-2 Porthos case study

The Porthos case study was used to compare the REX-CO_2 screening methodology and tool results against a detailed assessment conducted for a real-world Carbon Capture and Storage project. The field contains six existing wells, of which three are intended to be re-used for injection and one to be maintained as a backup well. The total capacity of the field is around 32 million tonnes of CO_2, which accounts for almost 75% of the total capacity of the P18 block. The field is operated by TAQA, with CO_2 storage planned to be commissioned and operational by 2024/2025.

In support of the project, a detailed technical feasibility assessment for CO_2 storage in the depleted P18-2 field gas field was conducted (Neele *et al*., 2019). This assessment provides the main reference for comparison against the REX-CO_2 case study assessment. The well integrity assessment concluded that all of the wells that were intended for re-use have the potential to be used safely as CO_2 injectors if all identified risks are properly mitigated. The report also proposed appropriate mitigation measures to make them fit for storage operations. Those measures include replacement of current retrievable packers and completions in all wells, potential recompletion below the current packer depths, and in one case the abandonment of a sidetrack. Additionally, all materials should be checked for suitability to the expected low temperatures, all leaking pack-offs and seals should be replaced, load cases for CO_2 injection should be assessed, and detailed corrosion assessments should be undertaken.

Application of the REX-CO_2 screening tool to the Porthos case study identified issues and mitigation requirements consistent with those identified by Neele *et al*. (2019). The tool provided an indication of the degree of workover and recompletion required. Workover operations would also provide an opportunity to address some of the remaining uncertainties through additional logging and verification of well barrier effectiveness. As also identified by Neele *et al*. (2019), the uncemented liner lap section was identified as an outstanding issue. The verification methods and risk management strategies suggested by Neele *et al*. (2019) are expected to be required to mitigate the associated integrity risks identified through use of the REX-CO_2 tool.

The Porthos case study therefore provides confidence in the performance of the REX-CO_2 screening tool and in the qualitative assessments provided through its use.

4.2. Common data gaps

Despite data availability issues encountered during several of the case studies, currently available data have proven to be helpful in obtaining a first impression of the status and potential for re-using wells in all cases. The case study assessments have provided valuable insight into the critical areas requiring further investigation. Identification of data gaps can be used to direct engineering capacity towards particular well barrier elements requiring specific attention.

Structural integrity represented a significant uncertainty across the suite of case studies evaluated in the REX-CO_2 project. It is rarely possible to assess issues such as corrosion or lifetime load profiles of components integral to structural integrity, without access to operational records and experience of the field.

The predicted consumed life of the structural integrity components should be assessed along with the anticipated lifetime load profile associated with the CO_2 storage project. The remaining functional life of the combination of structural components should be suitable for the anticipated project. This assessment requires input from prospective CO_2 storage operators, including detailed injection profiles.

It is likely that the current status of critical components would need to be assessed in order to validate structural integrity. It is important to recognise that conducting structural integrity surveys for offshore wells is a costly and technologically challenging process.

The quality of the cement sheath and casing corrosion status presented significant uncertainty in several of the case studies. Most of the information required to verify the cement and casing integrity can be acquired by running logs and/or verifying well barrier effectiveness during workover operations following removal of tubing. In some scenarios, it may be recommended to run cement evaluation logs whilst pressurising the cement sheath, to enable comparison with the original logs. Amplitude changes may be indicative of cracks, microannuli, debonding, or mud pockets that may provide potential migration pathways.

Uncertainty with respect to dual-cased sections is expected to remain, as it is difficult to evaluate the quality of cement in such circumstances using currently available technologies.

Where uncertainties remain following an assessment of currently available data, it is recommended to consider the actions that could be taken to acquire additional information about the well to understand the current well integrity status. Some data, such as those obtained by cement/casing evaluation logging cannot be readily acquired without removing tubing. The costs associated with such intervention may be mitigated where such logging is a requirement of the decommissioning process. Depending on the uncertainties associated with a given well, some additional information may be acquired with relatively little effort and before decisions are made to commence workover operations. Examples include integrity tests on tubing, packers, X-mas tree, and wellhead seals, valves and connections. Annulus pressure monitoring may also be considered if not already undertaken. Such actions may be recommended on a case-by-case basis to enable a comprehensive screening assessment to facilitate decision making.

4.3. Considerations for repurposing wells

A key finding from the case studies evaluated in REX-CO_2 is that significant intervention would be required to re-use all of the wells evaluated. The extent of the interventions is defined by the severity of the expected remediation or risk management strategy. The case study analyses indicate that a drilling rig or workover unit is usually required in order to repurpose wells, including replacement of production tubing and packers, as well as upper completion components such as X-mas trees and wellhead tubing spools. In some cases, remediation could be achieved with no rig requirements, via wireline or coiled tubing interventions, however a rig or pulling unit will be required to remove tubing in order to enable evaluation logging. Material incompatibility of completion and packer operating envelopes are indicated in the majority of the case studies.

Primary barrier components which may be subjected to Joule-Thomson cooling effects, are unlikely to be rated for extremely cool temperatures, requiring consideration in re-purposed well designs. The completion will need to be suitably adapted for the pressure and temperature loads anticipated during CO_2 storage operation. Packer depths should be assessed and relocated if required to ensure well integrity.

Much of the uncertainty identified from the case studies relate to the integrity of the cement sheath and casing. It is recommended that verification efforts such as cement/casing evaluation logging are undertaken. In most case, these additional logs can only be acquired following removal of the completion or primary barrier envelope. If cement quality cannot be qualified as a barrier, and could cause leakage problems, dedicated remedial cementing methods should be applied, for example cement squeeze. In case of severe issues, or “B” annulus problems, remedial methods would consider casing and cement milling, placement of cement plugs and running new casing. This necessitates the adoption of a risk management process for the conversion that considers what is known, or can be determined at present, whilst also recognising the uncertainties that can only be addressed following commencement of a well's conversion process.

Many of the issues and uncertainties identified concern the integrity of the primary barrier elements. Whilst the primary barrier integrity is evaluated as part of the REX-CO_2 screening process, it is clear from the case study analyses that the majority of the primary barrier elements would need to be replaced when repurposing a well. The integrity of the secondary barrier is therefore of greater criticality, as secondary barrier elements such as production casing and liners are less readily replaceable. Where integrity concerns are identified, effective risk management approaches will be required to assess if irretrievable secondary barrier elements prevent re-use of the well. Key issues identified, and recommendations for verifying and re-purposing existing wells are summarised in Table 6.

Table 6. Key issues and recommendations determined through case study assessments.

Key issues	Recommended actions
Tubing and other downhole completion equipment not suitable for CO_2 storage (not rated for anticipated chemical environment or low temperatures)	Recomplete well with CO_2 compatible completion equipment to enable injection/monitoring
Near-surface equipment including X-mas trees, tubing spools and tubing hangers not rated for low temperatures	Replace upper completion equipment
Issues related to poor and/or unknown cement quality: 1. Behind packer 2. Of overlapping cements 3. Of production casing/liner	In all cases it is recommended to run cement evaluation logs and/or perform other integrity tests Depending on the severity of the cement problem, apply adequate remedial methods such as repositioning packer at the level of good quality cement within the caprock, cement squeeze, and in the worst-case cement milling, plugging and running new casing
Corrosion status of casing uncertain	Run corrosion logs or perform other integrity tests
Limited data available to verify structural integrity	Obtain information from field/well operator. It may be necessary to undertake structural integrity surveys if the well is considered for re-use
Certain data for barrier verification commonly not available (i.e., annulus pressure history, recent barrier verification records etc.)	Work with site/well operator to obtain data and establish effective processes for data/knowledge transfer Identify prospective wells early and commence discussions around potential re-use in advance of field closure (potential application of the REX-CO_2 tool for first-pass screening and identification of missing data)
Qualitative/subjective assessment is unavoidable for older wells (inconclusive logs, operational results subject to interpretation)	A fresh suite of measurements and barrier verifications should be acquired

The recommendations provided in Table 6 provide an indication of the activities that may commence following initial screening, and may influence feasibility studies, design and workover operations.

Where wells are not intended to be re-used for CO_2 storage, attention should be given to the permanent plugging and abandonment plans, as this may affect the integrity of the site for CCS. It would therefore be of benefit to identify if a given well is located in a location where special consideration of future CO_2 storage site integrity might be impacted. This will enable consideration of future CO_2 storage operations in decommissioning plans. This is already a requirement in some regulatory settings, where petroleum licence operators must ensure and be able to demonstrate that all viable options for continued use (including re-use for CO_2 storage) have been suitably explored. Designing permanent plug and abandonment plans in such a way as to ensure integrity during future operations, including CO_2 storage, are included in these obligations.

5. Other re-use scenarios

5.1. Saline aquifers

Saline aquifers present different challenges for well re-use when compared to oil and gas wells. A key issue is that fewer data are generally acquired from non-productive strata such as saline aquifers and their top seals. Where saline aquifers are present above or below productive oil and gas reservoirs, it is unlikely that significant data or samples are available to characterise the mineralogy and water chemistry in detail. Lack of water samples can be particularly problematic as they are required for corrosion and metallurgical studies.

Exploration wells that penetrate saline aquifers are likely to have been permanently plugged and abandoned, and are generally not available for re-use. A further discussion of the issues relevant to re-use of abandoned wells is provided in Section 5.2. Evaluation of the integrity of such wells is a critical feature in the assessment of CO_2 storage site integrity.

The majority of wells penetrating saline aquifer formations will have been completed for production from hydrocarbon-bearing reservoirs beneath or above the aquifer. The saline aquifers of interest for CO_2 storage were historically considered as part of the unproductive overburden. These saline aquifers will therefore not be accessible without significant intervention, as access will be blocked by casing and cement. Such a case study site from the UK was evaluated in REX-CO_2 Deliverable D4.4 (Williams and Hoskin, 2021), and is summarised in Box 3.

Accessing the saline aquifer storage formation may require extensive milling or removal of existing casing and cement, and/or perforation, potentially using large charge sizes to penetrate dual-cased sections. The number of casing strings and the extent of cementing are key determinants of the potential for re-using such wells, and may be used as high-level screening criteria for well re-use. While surface and intermediate casing size is usually sufficient to enable workover activities to take place, casing specifications may lack the required material compatibility for use in CO_2 storage operations at shallower intervals. Other options such as sidetracking can also be considered as a means to re-use former oil and gas wells for saline aquifer storage. Sidetracking may offer an effective means to establish access to the saline aquifer whilst ensuring that all well materials subjected to CO_2-rich fluids and to rapid temperature fluctuations meet the recommended specifications. In such cases, the abandonment procedures for the parent well beneath the kick-off depth would need to be carefully considered to ensure integrity.

In some cases, the saline aquifer of interest may underlie the hydrocarbon reservoir, in which case the well may require deepening or sidetracking in order to access the saline aquifer for CO_2 storage purposes. The position of wells within saline aquifers will also require special consideration, and sidetracking may provide the optimal solution for effective re-use.

Box 3: UK saline aquifer case study

Williams and Hoskin (2021) evaluated well re-use potential for a Triassic saline aquifer sandstone formation which overlies a depleted gas field. Eleven of the gas production wells penetrating the site are currently shut-in and awaiting decommissioning. The re-use concept evaluated by Williams and Hoskin (2021) would involve partially plugging the well to isolate the hydrocarbon-bearing reservoirs, and accessing the shallower saline aquifer through the present intermediate casing string.

The number of cemented casing strings and liners across the intended saline aquifer storage formation are critical to the design concept. The oldest wells at the site employ a single intermediate casing with a liner hanger set below the saline aquifer, which would enable access to the aquifer through simple perforations. More recent wells run production casing to surface, with top of cement beneath the aquifer. These wells would require the production casing to be cut and removed above the top of cement prior to perforating the intermediate casing. The most recent wells however, have both production casing and/or tie-back casing fully cemented across the aquifer. This would require extensive milling operations or perforating with large charge-sizes to access the intended CO_2 storage formation. The number of casing strings and extent of cement across the saline aquifer unit may therefore provide a rapid screening criterion to evaluate the amount of work required to re-use wells in saline aquifer formations.

In this re-use design concept, the present intermediate casing string essentially becomes the production casing for the re-purposed well. However, current casing steel grades in the overburden do not meet the minimum specifications as recommended by REX-CO_2. While this may be manageable with appropriate operations and maintenance work, it is likely that higher grade steels will be desirable, particularly as the casing will be exposed to wetting reservoir fluids. While it is possible that the risk could be managed effectively given that the primary caprock section is completely cemented, this raises considerable concerns over well integrity. Alternatively, once the tubing is removed there is sufficient space available given the intermediate casing diameter to install a new production casing and liner, removing the criticality of the present casing in the well barrier design. A further option would be to plug the saline aquifer interval and to sidetrack the well, using materials graded appropriately for CO_2 storage, to reduce the risks to as low as reasonably practicable.

The saline aquifer in question represents a significant storage resource, with storage potential distributed at several sites across a wide area (Noy *et al*., 2012). The hydraulic behaviour of the regional aquifer system remains a key uncertainty that will impact the management of the formation for CO_2 storage. If storage operations are to commence in the region, access to far-field well pressure monitoring data would be of significant value in addressing hydraulic behaviour. This aquifer pressure monitoring concept may present the most promising opportunity for re-using existing wells in saline aquifer settings, if the intended storage reservoir can be accessed. If located carefully, exposure of such wells to both CO_2-rich fluids and to significant cooling can be avoided, removing the material compatibility constraints identified by Williams and Hoskin (2021). It is recommended that the option to re-use wells to monitor the far-field response of hydraulically-connected saline aquifer formations to CO_2 storage operations is further explored.

5.2. Abandoned wells

Re-using wells that have been permanently plugged and abandoned is expected to be a costly and challenging process, particularly in offshore settings. The Romanian case study, described in REX-CO_2 Deliverable D4.6 (Dudu, 2022), referred to the re-use of abandoned onshore hydrocarbon wells from the Salonta structure, an onshore depleted gas field. The case study concluded that it is unlikely the wells could be re-used in an economic and technically secure manner.

In most abandoned well settings, the surface installations are likely to have been removed, and multiple abandonment plugs will block access to the relevant parts of the well. In offshore settings it will be particularly challenging to re-access abandoned wells. Wells that have had their wellheads removed, or otherwise compromised, are highly unlikely to be re-useable. As the anchor for structural casings, the wellhead cannot be replaced or remediated. Re-use following abandonment would require that there is a programme in place to maintain the wellhead from corrosion, degradation, accidental, or intentional damage.

Abandonment plugs will need to be removed in order to access the wellbore down to at least the depth of interest for CO_2 storage. The substantial task of removing abandonment plugs to access wellbores with little knowledge of present-day conditions is likely to be prohibitive. In addition, record keeping for legacy abandoned wells may not be complete, particularly for older wells. There may also be significant uncertainty over the abandonment status of the well, for example the depth of cement plugs. There will also be a lack of recent inspections and verification. In the absence of recent integrity assessments, probabilistic modelling approaches could be employed to provide indications of well integrity to aid decision-making (Orlic *et al*., 2021). While such tools may provide an indicative tool, further experimental studies are required to improve model calibration and predictive capability to aid decision making.

Given the technical issues identified above, it is not anticipated that re-use of permanently abandoned wells is likely to become commonplace. However, if abandoned wells are identified as potential risks to a particularly high-value CO_2 storage site, it may be necessary to attempt to re-access the well for remediation purposes. In this case, the merit of re-use could potentially be reappraised.

5.3. Re-using wells for monitoring

Many of the technical requirements and screening criteria described in Section 3 will equally apply to dedicated monitoring wells. Depending on the location of potential wells with respect to the anticipated chemical, pressure and temperature conditions in and around the reservoir, the critical importance of certain material compatibility requirements may be reduced. Considerations include:

- The intended purpose and scope of well-based monitoring;
- Whether the well will be contacted by the CO_2 plume or affected by acidic fluids;
- The degree of pressure increase expected at the well locality;
- Proximity to the region affected by thermal stresses in the vicinity of injection wells.

It should be borne in mind that even if the well is not re-used as a dedicated monitoring well, opportunities for acquiring monitoring data could arise during workover operations and during subsequent routine maintenance. As per the UK saline aquifer case study described in Box 3, far-field or offset wells may potentially be re-used for monitoring at comparatively low risk, relative to wells located within the anticipated plume footprint. Such wells will however have reduced scope for monitoring conditions at the CO_2 storage site. A suggested workflow for assessing the high-level potential for re-use of wells for monitoring is provided in Figure 5.

Following identification of wells with monitoring potential, a feasibility study would be required to assess which technologies might be effective at detecting the expected physical and/or chemical changes resulting from CO_2 injection and storage at the specified well location. It would be necessary to assess whether the wells have the required physical space and opportunities to run, install and maintain and retrieve the selected equipment. Consideration of data communications is also required. Memory gauges require retrieval to access the recorded data, and for more permanently installed set-ups, communications from the equipment to sea surface/operator need to be planned for. Some considerations for different monitoring technologies are provided in Table 7.

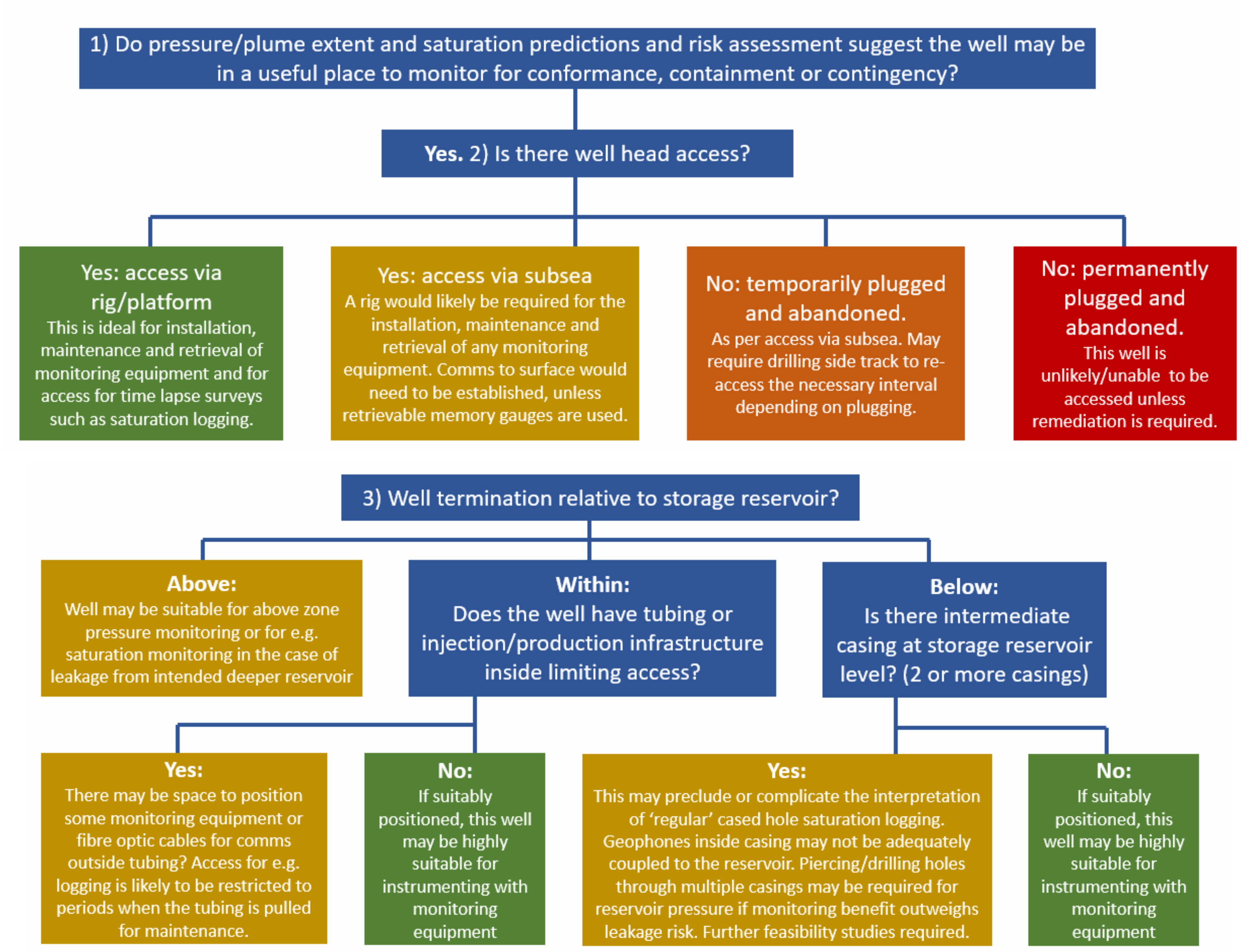
A cost-benefit analysis would also be required, to weigh up the value of the monitoring activity in relation to the expected costs and any associated risks. This will be highly case specific.

Table 7. Considerations for suitability of monitoring technologies in re-used wells. The technologies, measurements and practicalities are based on known hazards and risks, operational issues, potential benefits and past experience, and are not intended to be exhaustive.

Technology	Measurements	Some practicalities
Along-borehole sensing with fibre optics (permanent installation with continuous output)	Pressure Temperature using Distributed Temperature Sensing (DTS) Distributed Acoustic Sensing (DAS) in passive listening mode or active using a seismic source on the seabed/boat Strain (cylindrical wrap around casing)	Usually installed outside casing so unlikely to be applicable to reused wells unless casing is pulled and reinstalled (assumed that installing inside casing would provide insufficient coupling to formation in most cases) Perceived possible integrity risk ('weakness' in cement that migrating CO_2 might exploit) Possibility of damage on installation, requires careful set up If able to install, minimal subsequent access is required, can be very cost effective. Large volumes of data generated: transfer, storage, processing burden and impact on reservoir management
Downhole sensors installed at discrete depths in well (semi-permanent, retrievable, continuous output accessible in real-time or on retrieval, i.e. memory gauges)	Pressure Temperature Tiltmeters Seismic geophones etc.	Pressure sensors have been installed in all CO_2 storage injection wells to date, except Sleipner (wellhead pressure only) Pressure measurements require access to the formation (e.g. via perforations), and geophones require good coupling to casing and the formation Multiple casing strings, or poor casing-cement-formation bond may preclude use Requires wellbore access for installation, maintenance and retrieval. Permanent sensors can have a 10-year life, whereas memory gauges can store up to a single year's worth of data Measurement drift possible if gauges not regularly calibrated

Individual surveys using downhole logging (one-off or time-lapse surveys; real-time data during logging via cable)	Saturation (pulsed neutron capture etc.) Wellbore integrity (cameras, calipers, cement evaluation logs etc.)	Requires rig and wellbore access of sufficient unrestricted diameter to allow tools to pass. Potential to log during maintenance periods, for example if tubing is pulled Saturation can be measured through casing, however the sensor has a limited depth of investigation Monitoring for CO_2 wellbore breakthrough requires appropriately timed surveys Saturation logging can be complicated by halite precipitation (Baumann *et al*., 2014) Build-up of mineral scale can obstruct logging (Vandeweijer *et al*., 2004)
One-off or time-lapse surveys (real-time data during sampling or via lab analyses)	Pressure Fluid sampling (e.g. CO_2 saturation, tracer detection, geochemistry)	Requires wellbore access and appropriately timed surveys Tools such as the Cased Hole Dynamics Tester (CHDT) can drill though casing and cement, take measurements and up to six fluid samples, and subsequently plug the hole (6-inch maximum penetration) Perceived well integrity risk, although plugged holes are rated Cost depends on complexity of required analyses. Onshore cost per sample at a pilot site was of the same order as per specialist PVT analysis (£5–10k GBP per sample after IEAGHG, 2015) An experimental semi-permanent u-tube setup has been used successfully onshore Gas lift, pumping or production stream samples can be acquired if access to wellbore tubing/pumping equipment

Figure 5. Recommended high-level considerations for evaluating potential to re-use existing wells for monitoring at CO_2 storage sites. Wells that fall into the green boxes may be the most suitable, while those in orange boxes could be suitable if the limitations are overcome. Those in red boxes are unlikely to be re-used for monitoring except under exceptional circumstances.


1) Do pressure/plume extent and saturation predictions and risk assessment suggest the well may be in a useful place to monitor for conformance, containment or contingency?
Yes. 2) Is there well head access?
Yes: access via rig/platform
This is ideal for installation, maintenance and retrieval of monitoring equipment and for access for time lapse surveys such as saturation logging.
Yes: access via subsea
A rig would likely be required for the installation, maintenance and retrieval of any monitoring equipment. Comms to surface would need to be established, unless retrievable memory gauges are used.
No: temporarily plugged and abandoned.
As per access via subsea. May require drilling side track to re-access the necessary interval depending on plugging.
No: permanently plugged and abandoned.
This well is unlikely/unable to be accessed unless remediation is required.
3) Well termination relative to storage reservoir?
Above:
Well may be suitable for above zone pressure monitoring or for e.g. saturation monitoring in the case of leakage from intended deeper reservoir
Within:
Does the well have tubing or injection/production infrastructure inside limiting access?
Below:
Is there intermediate casing at storage reservoir level? (2 or more casings)
Yes:
There may be space to position some monitoring equipment or fibre optic cables for comms outside tubing? Access for e.g. logging is likely to be restricted to periods when the tubing is pulled for maintenance.
No:
If suitably positioned, this well may be highly suitable for instrumenting with monitoring equipment
Yes:
This may preclude or complicate the interpretation of 'regular' cased hole saturation logging. Geophones inside casing may not be adequately coupled to the reservoir. Piercing/drilling holes through multiple casings may be required for reservoir pressure if monitoring benefit outweighs leakage risk. Further feasibility studies required.
No:
If suitably positioned, this well may be highly suitable for instrumenting with monitoring equipment

6. Policy, regulatory and social considerations

Current national regulations relating to well re-use in six countries (The Netherlands, Romania, France, UK, USA and Norway) were reviewed to develop an understanding of the regulatory and policy landscapes governing the re-use of existing wells (Dudu *et al*., 2020; 2021). Aside from the USA, the re-use of existing well infrastructure for CO_2 storage operations is not specifically considered in current regulations. Class VI Underground Injection Control regulations in the USA identify requirements for converting existing oil and gas wells for CO_2 storage operations. Several other countries have considered, and in some cases are still considering, the development of specific legislation and related policies for re-use.

Despite this paucity of specific legislation, there are practically no barriers to consideration of well re-use in CO_2 storage permit applications, especially where cessation of hydrocarbon production is followed immediately by transition to a CO_2 storage project. Different scenarios where re-use of wells might be considered for CO_2 storage are illustrated in Figure 6. Most regulatory barriers are likely to be encountered in cases where there is a time-gap between cessation of oil and gas operations and commencement of CO_2 storage operation. This may be particularly problematic where a separate CO_2 storage operator wishes to assume responsibility for a current petroleum licence (Rycroft, 2022). If a CO_2 storage operator is not ready to assume liability for a site and its associated infrastructure, then the regulations may allow for decommissioning to be postponed. This postponement represents a risk since it is unclear who should assume the liability during hibernation period, and may only be acceptable where the potential CO_2 storage resource is considered to be of significant value. The risk should be mitigated and all efforts should be made to have a CO_2 storage operator in place prior to decommissioning. The issue of liability transfer was addressed in a recent UK Government consultation on infrastructure re-use for CO_2 storage (BEIS 2019; 2020).

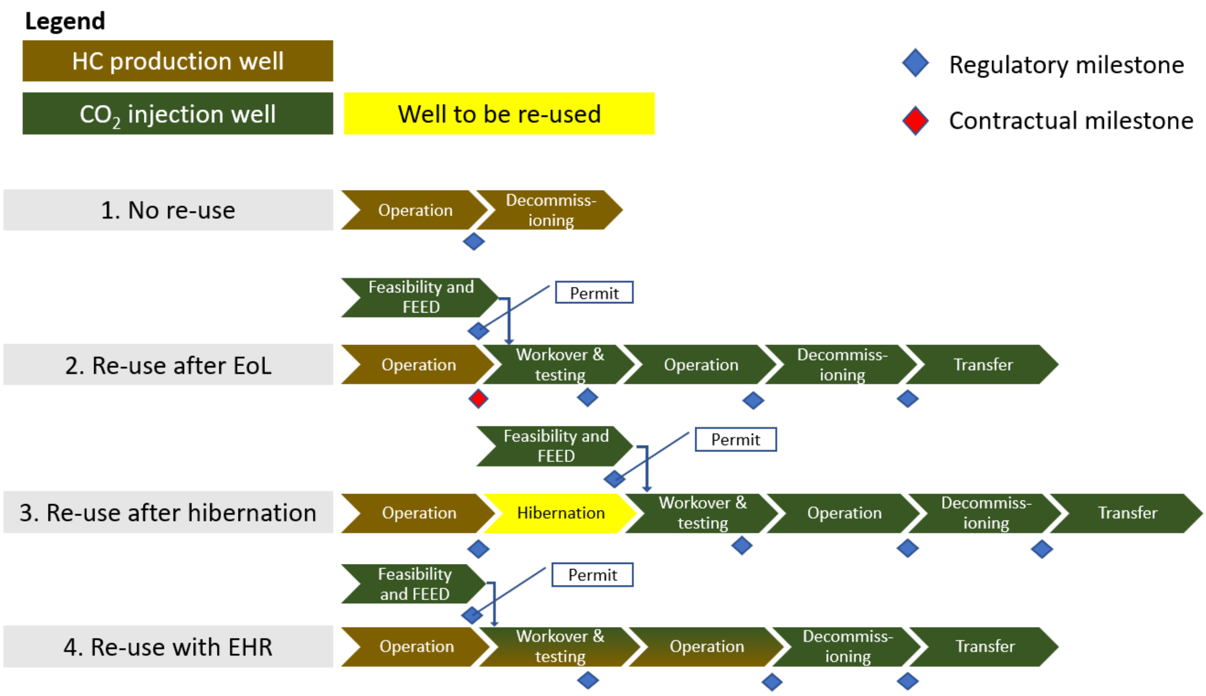


Figure 6. Timeline and milestones for different scenarios regarding well re-use for CO_2 storage after Dudu et al., (2021). EoL: End of Life, EHR: Enhanced Hydrocarbon Recovery.

Governments and regulatory authorities could potentially play an important role in promoting storage potential and infrastructure re-use through making data from oil and gas operations more accessible to future CO_2 storage operators (Section 2). A possible way to improve the efficiency of data sharing would be to elaborate on publicly available storage atlases.

Accessible data relating to prospective storage resources can raise awareness among potential CO_2 storage operators, and enable identification of where the greatest re-use opportunities are located. Data sharing is a significant barrier in many countries, particularly those lacking public storage resource databases. This can inhibit systematic identification of suitable storage sites. Public databases are also essential to facilitate research and to assess CO_2 storage options at country or regional level.

A further recommendation for encouraging infrastructure re-use is that hydrocarbon operators should conduct re-use assessments prior to commencing the decommissioning process. This may not need to be overly specific, rather operators should provide evidence that the potential for re-use has been considered. This is already a requirement in some countries such as Norway and the UK. Such an assessment should be a key point of ongoing discussions with regulators during the decommissioning process, but may not need to be a strict regulatory requirement in all cases. A clear understanding of the ranked distribution of potential CO_2 storage resources and of the potential deployment pathways would be helpful in guiding such discussions.

The REX-CO_2 well screening tool (Section 1.5) can be used to establish which wells have re-use potential and hence may help to overcome some of the identified regulatory barriers. Alongside databases of potential CO_2 storage sites, well screening information will allow oil and gas operators, or prospective storage operators, to make systematic assessments of potential re-use opportunities. This combination of clear information regarding storage resources combined with use of the REX-CO_2 screening tool, could assist regulators in judging whether to accept submitted decommissioning plans or to implement some means of preserving the assets. This may help to preserve key assets of national importance, reducing the risk of missing opportunities for re-use through decommissioning, or compromising future CO_2 storage operations through lack of consideration of CO_2 storage in plug and abandonment plans. The REX-CO_2 screening tool should only be used during the early screening process, as detailed engineering evaluations are required for full assessments.

Once further practical experience of well re-use is developed, additional guidance or legislation may be required on how well re-use projects should be undertaken.

Aside from the regulatory aspects, it will be important to formulate effective public communication strategies in order to gain public acceptance for future CO_2 storage projects. Lack of public acceptance has led to termination of projects in some regions. A public communication strategy for CO_2 storage projects involving well re-use is outlined in REX-CO_2 Deliverable D6.6 (Cangémi *et al*. 2022), and is based on the following framework:

- Define the objectives of the communication strategy (WHY);
- Identify and understand the target (WHOM);
- Find the positioning: STEP by STEP strategy;
- Define the communication style;
- Formulate the message to be communicated (WHAT).

7. Laboratory testing and future research

Well construction is subject to thorough international standards, which ensures a level of detailed understanding of the initial condition and properties of wellbore materials. The subsequent evolution throughout the life-cycle of a well complicates the understanding of how well materials will behave following their multifaceted operational history. In scenarios where the life of a well is to be extended by re-use for CO_2 storage, it will be important to understand the expected behaviour of well materials in response to the anticipated CO_2 storage operations. To address this knowledge gap, the REX-CO_2 project included an integrated laboratory and numerical modelling programme designed to simulate the state of materials in existing well systems. The aims were to assess the evolution of the physical and mechanical properties of wells, and to provide strategies for remediating any unplanned CO_2 migration that may occur if wells are re-used for CO_2 storage. The principal objective was to investigate well barrier degradation, well damage processes, self-healing mechanisms and remediation measures. The different experimental activities consider all the principal materials found within a well barrier envelope, including rock, cement and casing. However, evaluation of all potential conditions and processes was not possible within the scope of the project. The REX-CO_2 experimental activities are summarised by Ougier-Simonin (2020) and were focused on the following:

- Self-sealing of existing micro-annuli in casing-cement-rock systems;
- Downhole cement state of stress;
- Mechanical behaviour of cement-rock systems and interfaces;
- Remediation by microbial induced carbonate precipitation;
- Cement sheath temperature cycling.

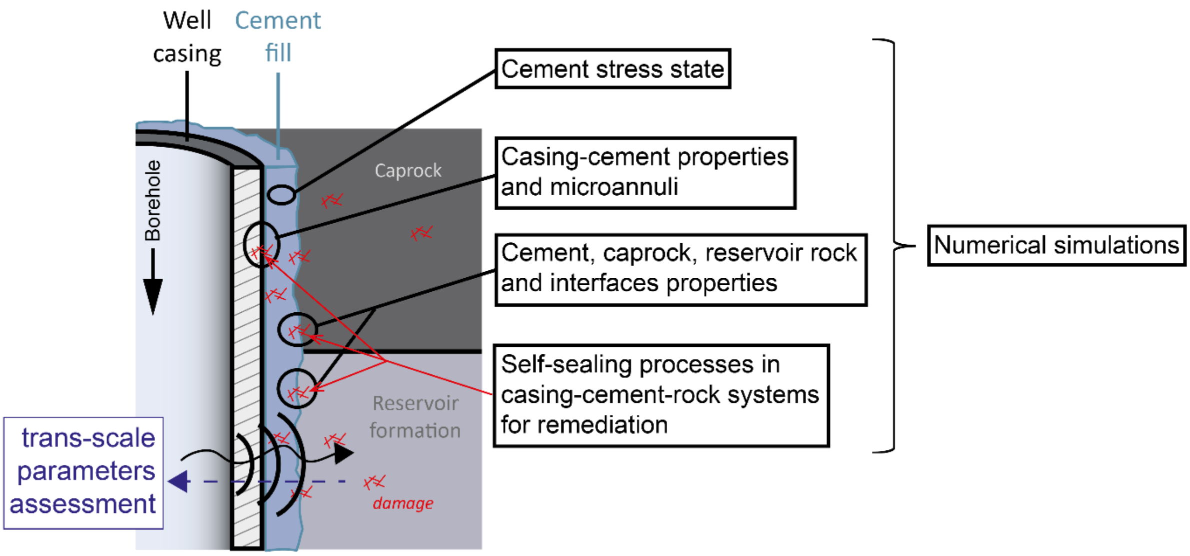


Figure 7. Schematic borehole system with indicated focus points of the REX-CO_2 experimental design.

The experimental studies focused on examining commonly encountered, relevant boundary conditions of the operational window where well integrity could potentially fail and/or be remediated. The diversity of experimental capabilities available across the partner organisations allowed targeting critical sections of the borehole system (as illustrated in Figure 7). The results provided information on the potential conditions that could be relevant for the wellbore materials prior to re-use, and ways in which minor integrity issues could be remediated to re-establish well integrity.

The range of conditions for which data were collected through laboratory experiments is limited compared to conditions commonly encountered in the field. A combined experimental and modelling approach enables simulation of most of the processes that may occur in wellbore environments. However, the data on actual and historic downhole conditions are either limited or missing. Improved logging of wells in combination with a publicly accessible database containing a wide range of wellbore environment conditions and wellbore material responses to those conditions, would benefit understanding of borehole conditions. This could be used to further extend applicability of laboratory data to assess the suitability of an individual well for re-use. Further experimental work should focus on performing tests across a large spectrum of downhole conditions and wellbore materials to enable population of a comprehensive database.

Section 7.1 outlines the key findings derived from the REX-CO_2 experimental programme, while Section 7.2 provides potential directions for further fundamental research.

7.1. Key findings and recommendations of experimental studies

The experimental programme addressed several key issues identified during the case study assessments described in Section 4. Recommendations based on the laboratory findings are provided in Table 8.

Table 8. Experimental results and recommendations related to issues identified in the REX-CO_2 case studies.

Borehole material	Issues identified in case studies	Laboratory findings and recommendations
Casing	Corrosion status of casing may be uncertain, and potentially difficult to assess	Not investigated in this project; corrosion status of casing following end of production lifetime, including its impact on mechanical integrity, should form a focus for future research (see Section 7.2)
Cement	1. Logging or other data may indicate that cement is of poor quality, requiring remediation	Determining leakage rates that account for the stresses and mechanical behaviour of cement in well systems should be prioritised. This can inform risk assessments associated with well re-use. There is also a need for improved assessments of the relationship between mechanical and hydraulic apertures of annuli in wells, in particular regarding the continuity of flow pathways. Down hole microbial-induced carbonate precipitation (MICP) technologies have potential applications in geotechnical engineering including the remediation of oil and gas wells for CO_2 storage. However, the applicability in tight porous systems, such as confining reservoir rock, caprock and interfaces between cement and host rocks remains challenging, and MICP currently remains a low readiness technology option for such applications.
	2. Quality and integrity of cement may be unknown and/or difficult to verify	Higher pressure conditions during cement curing increases the mechanical strength of cemented interfaces (Rossillon *et al*., 2022). This raises the

		prospect that the quality of wellbore cement and its sealing properties at the casing and formation interfaces can be predicted from knowledge of the pressure around the wellbore during the operational life cycle of the well.
Well system	Condition of wellbore materials may be unknown and/or difficult to verify, while some data related to initial drilling and completion is commonly missing, unavailable or poorly recorded (particularly in older wells)	State-of-stress experiments and simulation studies indicate that well integrity is more robust to thermal and mechanical stresses than previously understood (Agofack *et al*., 2021; Meng *et al*., 2021). However, there are limits, and experimental studies provide values of maximum thermal and mechanical stresses that wells can experience before incurring damage. Assessing whether candidate wells have operated within the safe window of operations/conditions is possible with sufficient data on well barrier materials and the production/injection history. Cycling tests on downscaled wellbore samples illustrate that the ratio between the stiffness of cement and of rock formations is important. For example, a softer formation with stiff cement is likely to experience damage from temperature/pressure cycling. Knowledge of the rock formation and cement properties enables the mechanical failure risk to be assessed in older wells.

Additional laboratory findings related to interfaces between steel casing, cement and rock are listed below:

- Halite seals are established as ideal caprocks in the hydrocarbon industry. However, testing of standard Portland G cement at surface conditions failed to generate halite-cement interfaces with satisfactory mechanical characteristics. To characterise representative mechanical properties of halite-rock interfaces, there is a need for further laboratory experiments using appropriate cement formulations at in situ conditions;
- Numerical modelling and analysis of push-out-tests and tension tests indicates that the cohesion of cement-steel interfaces is between 1 and 4 MPa, while sandstone-cement interfaces are between 1 and 3 MPa. The analysis of push-out tests is less straightforward as they combine adhesion and frictional strength. The adhesion force in the shear direction is around half of that in the normal direction for steel-cement interfaces, and almost the same for sandstone-cement interfaces where most of the shear strength is provided by friction. This however, relies on the friction coefficients given in the simulation. Derived results show good agreement with those reported in the literature. The complexity of this geomechanical behaviour indicates a need for further research to improve understanding of the multiaxial response of the interfaces and to better derive the effects of rupture in tension and in shear. The implications would be that these tests should be further refined and standardised;
- Exposure to CO_2 increases the interface mechanical bond strength whatever their integrity, except in cases of steel/cement interfaces in dry CO_2 environments. CO_2 exposure in dry environments results in reduced mechanical integrity at the cement/casing interface by introducing radial cracks in the cement and decohesion of the steel/cement interface during aging. This finding is in keeping with similar CO_2-exposures tests where certain exposure conditions provide improved mechanical

properties of bulk cement (such as higher Uniaxial Compressive Strength and Young's modulus). Exposure to dry CO_2 would be less common, therefore the general implication is that cement as a well barrier material provide sufficient sealing capacity. Cement self-sealing analysis could be incorporated in future well leakage risk assessment frameworks that include pressure, temperature and chemical cement-CO_2 fluid interactions under the specific CO_2 exposure conditions.

7.2. Future research directions

Based on the REX-CO_2 experimental programme, the following research activities are recommended for consideration in future research programmes:

- Testing of the cemented interface to provide failure criteria, either by shear bond or tensile strength. These tests would provide valuable inputs to numerical simulations for assessing the likely performance of re-used wells. These criteria or damage-based models could be introduced in larger scale wellbore integrity simulations to provide new information or understanding in 3D numerical simulations. However, there is a need to achieve a stronger integration of new experimental results (such as thermal-hydraulic-chemical-mechanical behaviour) in numerical models to forecast well integrity issues given the full operational history of the well;
- The behaviour of the interfaces is strongly conditioned by the initial stresses during the cement curing process. It would be beneficial to better understand the behavioural physics of cement during curing in order to consolidate the interpretation of push-out tests and mechanical characterisations. Whilst this aspect was partially addressed in the REX-CO_2, the discussion needs to proceed further. A potentially useful outcome would be a specific modelling exercise for the curing phase;
- Progressing understanding of the impact of temperature on well integrity requires testing of the mechanical interfaces during temperature loadings of the interfaces, either be shear bond or tensile strength. An injection/storage well will experience temperature changes, and it is important to map how this can impact the integrity of the interface between the cement and rock/casing;
- The impact of local yet significant temperature changes (i.e. from local thermal gradient of oil and/or gas reservoir to freezing conditions due to dense-phase gas Joule Thomson cooling) should be investigated in laboratory studies to quantify the thermo-mechanical behaviour of the system in these expected conditions, both for safety (leakage) and sustainability (lifetime) purposes;
- Complementary studies are required to develop a comprehensive understanding of the mechanical performance of existing wells for re-use, as a result of variations in stresses due to coupled thermo-chemo-mechanical effects. The experiments in this project have quantified the CO_2 ageing effect on the mechanical strength of interfaces under a limited set of conditions. Additional information acquired under a wider range of conditions would improve understanding of the potential states and behaviours of material interfaces following varying periods of operation (integrity, self-selaing mechanisms, micro-annuli etc.). Additional experimental conditions could include longer-duration exposure to CO_2-rich fluids, different exposure protocols, and the effect of uniform diffusion for specimens submerged in fluids compared to single-sided diffusion of cement samples;
- Urease hydrolysis is not appropriate in all environments. Microorganisms capable of induced carbonate precipitation via alternative metabolic pathways are required to fulfil the full potential of MICP as a geotechnical tool. We recommend continued testing of

microorganisms capable of MICP to establish a full understanding of their performances in different environments relevant to borehole conditions;

- The variation in casing properties has not yet been studied in temperature cycling experiments. Similarly, different casing geometries such as different casing or borehole diameters requires further investigation. These two topics would be relevant for achieving an improved understanding of the effect of temperature or pressure cycling for different wellbore dimensions. Building a catalogue of property and behaviour data in conditions relevant to well re-use for CO_2 storage, would broaden the impact of the initial REX-CO_2 programme.

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Appendix A. REX-CO_2 Technical Deliverables

Deliverable (with hyperlink)	Report Title
D2.1	Current state-of-the-art assessments and technical approach for assessment of well re-use potential
D2.2	Summary report of well assessment tool framework
D2.3	Report on the REX-CO_2 well screening tool
D2.4	Report on well assessment tool demonstration results and updates
D3.1	Cross-experimental methodologies and background results for assessing complex borehole conditions
D3.2	Conference paper on experimental progress on remediation treatments (Experimental study of cemented interfaces for applications in CO_2 storage re-using depleted oil and gas reservoirs & Screening microorganisms for remediation of wells via carbonate precipitation)
D3.3	Advanced laboratory setup to determine and verify cement sheath integrity
D3.5	Conference paper on upscaling simulations (Effect of casing stand-off on cracks creation around the wellbore)
D3.6	Failure mode assessment and tubing material performance for CCS applications
D4.1	Re-use assessment of a potential CO_2 storage site in the Netherlands: Porthos
D4.2	Re-use assessment of a potential CO_2 storage site in the USA: the Vacuum Field
D4.3	Re-use assessment of a potential CO_2 storage site in Norway
D4.4.1	Re-use assessment of a potential CO_2 storage site in the UK: Bunter Sandstone
D4.4.2	Re-use assessment of a potential CO_2 storage site in the UK: Irish Sea
D4.5	Re-use assessment of a potential CO_2 storage site in France: the Rousse Case
D4.6	Re-use assessment of a potential CO_2 storage site in Romania
D4.7	Re-use assessment of a potential CO_2 storage site: Wintershall Dea case study
D5.1	Recommendations for re-using existing wells for CO_2 storage
D6.1	Report on the assessment of policy, legal and environmental framework
D6.2	Comparative analysis of regulatory frameworks
D6.3	Recommendations for Improvement of Legal and Environmental Framework
D6.4	Guidance for Mitigating Potential Regulatory Barriers
D6.5	Assessment of stakeholder and public perception of well re-use for CO_2 storage
D6.6	Public communication strategy for future projects involving well re-use for CO_2 injection/storage