Deliverable D1.7

Final Report

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Executive summary

This report provides an overview of all planned and achieved deliverables, milestones and activities for each Work Package of the REX-CO2 (Re-Using Existing wells for CO2 storage operations) project at a relatively high level. It is intended to act as a reference document to reflect on the entire project program and to report technical, non-technical and process-related deliverables, learnings, and impact.

The report also describes the project's contribution to the ERA-NET ACT2-call goals of international collaboration and accelerating the implementation of CCUS by providing results relevant to the industry and policy makers.

Lastly, a discussion on the outlook / future of the project main deliverable (e.g. Well Screening Tool) is included, which is based on several feedback sessions from (industry) partners and interested organisations.

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1. About REX-CO2

1.1. Introduction

Substantial cost savings may be achieved by re-using existing oil and gas infrastructure for CO_2 Capture, Utilization and Storage (CCUS). An increasing number of oil and gas reservoirs are approaching the end of their productive lifetime, presenting an opportunity for conversion of the facilities to enable CCUS (DOE, 2017). The existing wells in these assets present both an opportunity and a challenge for CCUS development. Substantial cost-savings could be achieved by re-using wells for CO_2 injection, monitoring or pressure management. Re-using wells can also offset the significant costs associated with decommissioning of offshore oil and gas infrastructure or drilling new offshore wells solely for CO_2 storage. Conversely however, existing wells pose a risk as potential CO_2 or brine migration pathways (Watson and Bachu, 2009). While the integrity and remediation of abandoned wells has been the focus of several previous studies (Carey, 2013; Wiese et al., 2019, Carroll et al., 2016; Sminchak et al, 2016), this project will for the first time assess the potential for re-using existing wells at scale in the context of CCUS. The re-use of wells is the inverse of the problem of identifying defective wells. The process of certifying well integrity can therefore also be used to identify wells that are suitable for continued use in a CO_2-rich environment. Some degree of workover or remediation is expected to be required to enable existing wells to be safely repurposed for CCUS.

We have developed a qualification process that will simultaneously reduce time and cost for developing CO_2 storage projects by identifying existing well infrastructure suitable for re-use. For wells identified with re-use potential, we have determined the workover and remediation requirements to ensure their long-term efficacy. Re-use can benefit projects in all geological settings but may be particularly important in offshore environments such as the North Sea or the Gulf of Mexico, where new well development costs might otherwise prove prohibitive. The development a procedure and tools for evaluating the re-use potential of existing wells did require a dedicated investigation encompassing the interrelated technical, environmental, economic, regulatory and social aspects.

For this project, we have developed a publicly-available, dedicated well-screening-tool for **Re-using EXisting Wells for CO_2 storage operations (REX-CO_2)**. Currently no such publicly-available tool exists. The tool will inform decision-makers on re-use of existing well infrastructure to accelerate CCS technology deployment through reduction of project and decommissioning costs for industry and regulators. Tool development is underpinned by laboratory validation and numerical modelling of fundamental processes, and its practical applicability has been ensured by inclusion of industry and regulatory bodies within the consortium. Application of the tool has been demonstrated through 9 dedicated case studies for representative wells from a selection of hydrocarbon fields and CO_2 storage sites. The case study sites represented different geological settings across six international regulatory authorities. The Tool is underpinned by recommendations from technical, regulatory and techno-economic aspects of re-using existing wells for CO_2 storage.

1.2. Overall aims and objectives of the project

The overall aim of REX-CO_2 is to provide decision makers with mechanisms and information to evaluate re-use potential of existing oil and gas well infrastructure. Based on state-of-the-art practices, standards, guidelines and international reference projects (Project Deliverable Report D2.1, Opedal, Greenhalgh, & van der Valk, 2020), the project has developed an assessment framework (D2.2, Pawar & van der Valk, 2020) which is translated to a stand-alone well screening tool (D2.3, Pawar, et al., 2021).

The Well Screening Tool can support in reducing costs associated with plugging, abandonment and decommissioning of existing wells, making individual project and large-scale developments more affordable. To achieve this aim, the specific objectives of the project are to:

- Enable operators and project developers to identify wells with high re-use potential by development of a well re-use assessment and screening-tool (WP2).
- Enable well re-use by determining the impact of previous well operations on wellbore materials and condition, together with the workover and remediation actions required for re-use (WP2-3).
- Remove barriers to re-use of infrastructure by testing new well remediation technologies and assessing the impact of well re-use on component material properties and well conditions through laboratory experimentation (WP3).
- Demonstrate potential value of well re-use applications by performing assessments on multiple candidate storage sites, distributed across seven international jurisdictions (WP4).
- Enable operators to develop effective well re-use plans in compliance with regulatory requirements, by developing a technical best practice recommendation document (WP5).
- Inform policy decisions through analysis of issues and concerns associated with regulatory, environmental and public acceptance aspects of well re-use for CCUS (WP6).

1.3. Project structure

The project has been organized to optimally address the Mission Innovation challenges in priority research directions (PRD) S-8 “*Locating, Evaluating and Remediating Existing Abandoned Wells*” and PRD S-9 “*Establishing, Demonstrating, and Forecasting Well Integrity*” and PRD CC 1-4.

The project structure includes seven work packages to achieve the defined goals (Figure 1), which are described in more detail in section 2. The administrative project activities are mainly addressed by two work packages: WP1 (Project management and coordination) and WP7 (Dissemination and communication). Work packages 2, 3, 4 and 5 are dedicated to the technical objectives of the project. The technical WPs are complemented by WP6 (Legal, environmental and social aspects), which investigated regulatory and socio-economic aspects of re-using existing well assets for CO_2 storage.

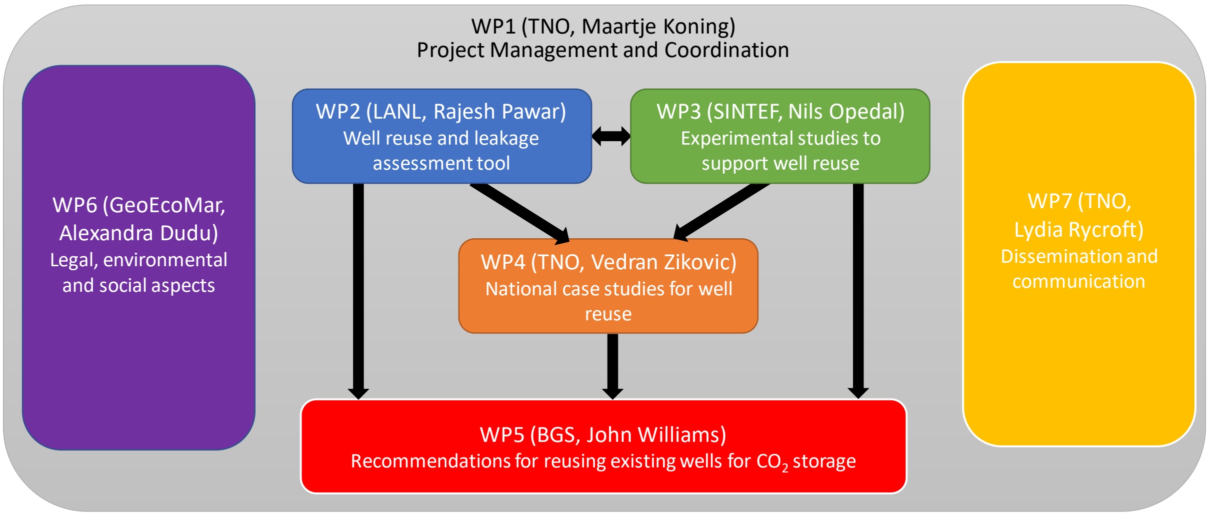


Figure 1: REX-CO_2 project structure with associated WP-Leads at project closure.

The management structure of the project was set up as per below figure, providing a firm framework for the complex and integrated activities of the project, while creating an open environment for (external) review and monitoring of project status / progress.

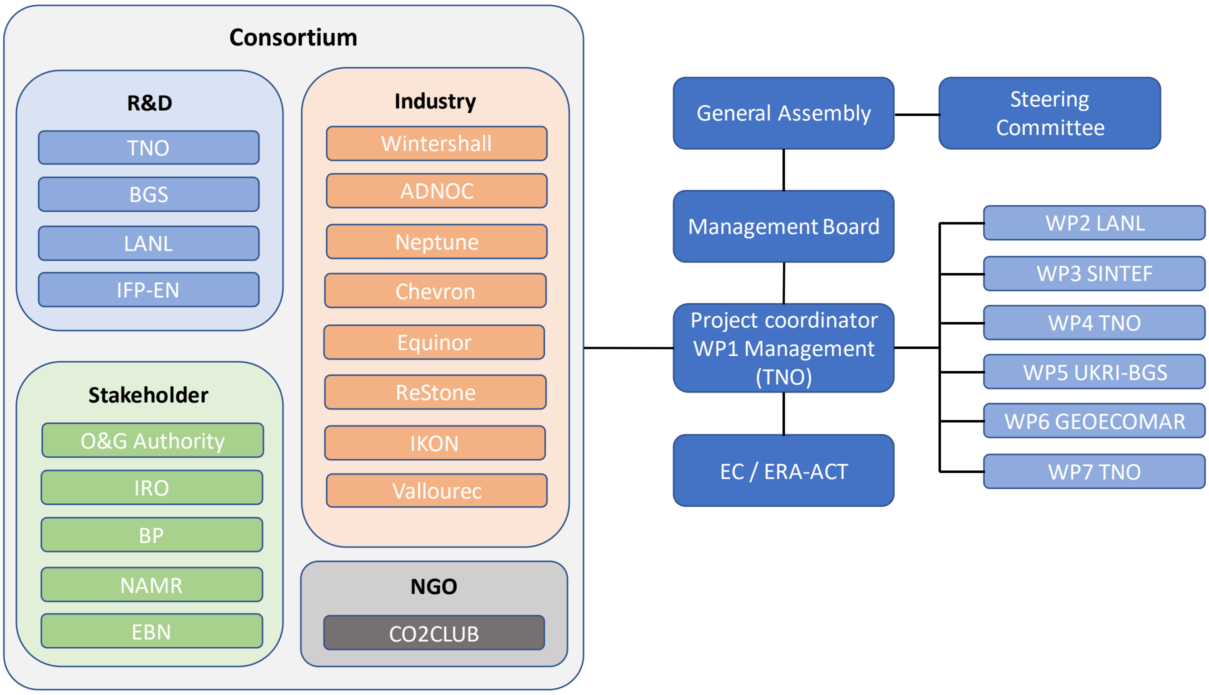


Figure 2: project management structure

1.4. Consortium

The consortium partners have been carefully selected to complement each other in terms of expertise and available laboratory equipment and connects organisations with a proven track record in CO_2 storage and well integrity research.

No.	Organisation	Country	Type of organisation	Role in the project	Comments
1	TNO (coordinator)	Netherlands	R&D	Coordinator, WP1, 4, & 7 lead	
2	SINTEF	Norway	R&D	WP3 lead	
3	ReStone AS	Norway	Industry, SME	Consortium Partner	
4	LANL	USA	R&D	WP2 lead	
5	Chevron	USA	Industry, O&G operator	Consortium Partner	
6	UKRI-BGS	UK	R&D	WP5 lead	
7	IKON	UK	Industry, SME	Consortium Partner	
8	GeoEcoMar	Romania	R&D	WP6 lead	
9	CO_2 Club	Romania	NGO	Consortium Partner	
10	IFPEN	France	R&D	Consortium Partner	
11	Equinor AS	Norway	Industry, O&G operator	Consortium Partner	
12	BP	UK	Industry, O&G operator	Stakeholder	
13	NAMR	Romania	National Authority for CO_2 geological storage	Stakeholder	
14	Oil & Gas Authority-OGA	UK	National Authority for CO_2 geological storage	Stakeholder	
15	IRO	Netherlands	Branch Organization of O&G service companies	Stakeholder	
16	EBN	Netherlands	Industry, O&G operator	Stakeholder	
17	Wintershall Noordzee	Netherlands	Industry, O&G operator	Consortium Partner	Joined in September 2020
18	Neptune Energy	Netherlands	Industry, O&G operator	Consortium Partner	Joined in March 2021
19	Vallourec Tubes	France	Industry, tubular manufacturer	Consortium Partner	Joined in December 2021
20	ADNOC	United Arab Emirates	Industry, O&G operator	Consortium Partner	Joined in April 2022

No.	Funding Agencies	Country
1	ERA-ACT	
2	French Environment & Energy Management Agency (ADEME)	France
3	Department for Business, Energy & Industrial Strategy (BEIS)	UK
4	Department of Energy (DOE)	US

5	Research Council of Norway (RCN)	Norway
6	Rijksdienst voor Ondernemend Nederland (RVO)	Netherlands
7	Executive Agency for Higher Education, Research, Development & Innovation Funding (UEFISCDI)	Romania

1.4.1. Role and contributions of each project partners

WP1 Coordination

TNO has led the project management and coordination efforts for REX-CO_2 ensuring proper execution of the Consortium Agreement and Project Plan. **TNO** has been the main contact to ACT for timely submission of deliverable and milestone reports, Traffic Light reports.

TNO has conducted several extra meetings & sessions with interested parties outside the consortium.

WP2 Well re-use and leakage assessment tool development

LANL has led the well re-use assessment tool development, which was co-developed and built by **LANL** and **TNO.** Contribution and support to the development of the tool was provided by **GeoEcoMar, UKRI-BGS,** and **IFPEN** contributing to the definition of the screening tool.

WP3 Experimental contributions

SINTEF has led the experimental work package and conduct experimental studies making use of its ECCSEL ERIC infrastructure as well as its rock mechanics laboratory. The main work scope was to study the influence of rock stiffness on cement sheath integrity and to developed numerical models to upscale laboratory results to integrate them into the numerical tool.

IFPEN has performed experimental characterisation of cement/steel interfaces with and without subjection to CO_2, and has developed numerical simulations of laboratory tests. The main work streams considered capturing the mechanical behaviour of the interface in order to assess the effect of various parameters on mechanical strength (e.g. curing pressure, halite & sandstone steel-rock interfaces. In addition, **IFPEN** studied the effect of CO_2 aging on interface mechanical strength (on shear resistance) for various conditions.

Restone provided the blend of various cement types required for the experimental program. In addition, they supplied remediation solutions and assisted with well integrity assessment.

UKRI-BGS has led the laboratory investigations of well and surrounding materials properties by evaluating mechanical behaviour of wellbore materials and remediation by carbonate precipitation by the presence of microorganisms.

Vallourec provided a state of the art report on material selection for CCS applications describing conditions expected in antropogenic CO_2 injection wells, the main challenges and recommendations for an approach for material selection.

TNO contributed to the main objectives in WP3 by providing experiments to (1) Trigger self-sealing of existing microannuli in casing-cement-rock systems by manipulating the local effective stress field through pore fluid pressure regulation; and (2) Numerical simulation (Finite Element Models) for upscaled analysis of well response to thermal and geomechanical stresses including self-sealing and the efficacy of remediation; and (3) MS14 Workshop on transferring results to re-use tool.

LANL contributed by running experiments to evaluate cement in situ properties and state of stress and linking this to safe operation conditions (e.g. temperature and pressure change limits) for safe well re-use.

Equinor has provide financial support and advice on national research priorities in Norway.

WP4 National well re-use case studies

TNO has coordinated the national case studies work scope and has performed Well Screening Assessments for the following case studies: Porthos P18 field, Adnoc, Neptune and Wintershall.

As stakeholders, **IRO** and **EBN** were involved in the selection and evaluation of the planned Dutch case studies, while **Wintershall** and **Neptune** were instrumental for the delivery of the extra Dutch case studies and reporting. **GeoEcoMar** has performed the Romanian case study. The US case study was conducted in coordination with **Chevron**. The UK case studies were assessed by **IKON**, with **BP** providing an industry stakeholder advisory role (for the entire project). **ADNOC** provided data and knowledge to support the extra case study in the UAE.

All industry collaboration directed national sub-objectives, and ensured appropriate results and tool performance from an end-user perspective**.**

SINTEF participated in the national case studies, conducting cost-estimate scenarios based on reservoir simulations incorporating new knowledge on well re-use cost savings and penalties.

WP5 Recommendations for re-using existing wells for CO_2 storage

This WP was led by **UKRI-BGS,** with input from **TNO, SINTEF, LANL, GeoEcoMar** and **IFPEN,** resulting in several milestone reports capturing the learnings and recommendations from the various work packages. **UKRI-BGS** coordinated the key deliverable report D5.1 describing and integrating all project recommendations on re-using existing wells for CO_2 storage.

WP6 Legal, environmental and social aspects

This WP was led by **GeoEcoMar,** which was responsible for the delivery of most project report deliverables. **GeoEcoMar** has worked closely together with **BGS, SINTEF, Restone, LANL, TNO, IFPEN and CO2Club Romania** to establish current legal, environmental and regulatory frameworks governing re-use of wells in the participating countries, as well as social aspects related to re-use.

WP7 Dissemination and communication

This WP was led by **TNO**, with contributions from **GeoEcoMar**, **UKRI-BGS**, **CO2Club**, **SINTEF** and **IFPEN**.

TNO set up and facilitated updates to the project website and social media. Delivery of the Newsletters was handed over from **CO2Club** to **TNO** after the first newsletter. Together with **SINTEF**, the project communication strategy was defined and executed.

GeoEcoMar organised the final dissemination event in collaboration with **TNO**. This event was a public webinar communicating main project findings in the context of CCUS in general.

2. Description of activities and results

2.1. WP1: Project management and coordination

The main aim of WP1 is to coordinate the work involved in the project, and to manage the project with respect to financial and contractual obligations. The objective is to ensure smooth and timely execution of the project scope through participation and involvement of all partners.

Task	Achievement
Task 1.1 Managing process of activating and executing the Consortium Agreement between the consortium (TNO)	Implemented and executed Grant & Consortium agreement, including amendments to Project Plan, IP considerations for Tool publication and accession of new consortium members.
Task 1.2 Administrative issues (TNO)	Timely submission of all deliverables, milestones and Traffic Light Reports.
Task 1.3 Management board and project meetings (TNO)	Conducted monthly Project Management Board Meetings with WP-leads. Conducted yearly General Assembly meetings, mid-term review meeting and final close-out meeting. Ensured close communication with industry and associated partners through steering committee, advisory boards, and external review sessions to get end-user perspective

2.1.1. Main results

The results shown in the following for each task in WP1 are as summarized in the public guideline reports, i.e., D1.1, D1.4, and D1.7

2.1.1.1. Task 1.1 Managing process of activating and executing the Consortium Agreement between the consortium

Task 1.1 involved managing the execution of the Grant and Consortium Agreement. The Project Plan was amended in Q3 2020 with minor changes to deliverable dates, titles and to remove a planned trial on unpromising technology (casing pulling tests) from the programme. All amendments have been approved by the General Assembly and Management Board and are captured in an updated Project Plan Amendment document.

During the project 4 new partners have accessed the Consortium: Wintershall Noordzee (joined in September 2020), Neptune Energy (joined in March 2021), Vallourec Tubes (joined in December 2021) and Adnoc (joined in April 2022), contributing either financially to the project or with in-kind contributions. The accession of new partners allowed for an expansion of the original project plan, with additional deliverables (e.g. 3 Case Studies), activities (e.g. extra updates on the Well Screening Tool), extra research (e.g. state-of-the-art knowledge/research on material compatibility & selection for re-use of wells for CO_2 storage), and additional dissemination (e.g. papers, conferences).

The legal & IP activities regarding the public release of the Well Screening Tool on the REX-CO_2 website have been managed by LANL and TNO, who own the IP rights of the Tool.

2.1.1.2. Task 1.2 Administrative issues

At the beginning of the project a Data Management Plan (D1.1) was constructed, describing the expected project data and types and how the data is made FAIR (Findable, Accessible, Interoperable and re-usable). All documents, deliverables, milestones and working files are shared among consortium partners using a secure Sharepoint site. All deliverables have been reviewed and approved by the consortium contact persons before submission to ACT.

The REX-CO_2 project strives for open access of data and results. Therefore, all deliverables as listed in the Project Plan have been published on the REX-CO_2 project website. The Well Screening Tool will become public and accessible through the project website September 2022.

Quarterly Traffic Light Reports (TLR) have been submitted to ACT, including project status and progress per WP's and a yearly overview of the financial situation and a list of publications and dissemination activities.

All Project deliverables and Milestone documents have been submitted to ACT in time (except D3.4, which was finalised in time, but submitted too late). WP-3 scope suffered from delays in activities due to COVID-19 restrictions at many of the participating laboratories. As a result, the topic of D3.1 was slightly altered and the date for D3.2 was postponed by 3 months. At the end of the project, all delays were caught up.

2.1.1.3. Task 1.3 Management board and project meetings

Monthly management board meetings have been conducted with the WP-leads, tracking and discussing progress, status, deliverables, actions, and flagging issues.

Yearly General Assembly and Annual meetings were conducted successfully with excellent feedback:

- 2020 Annual meeting, including General Assembly & Steering Committee meeting on 22-23 September 2020
- 2021 bi-annual workshop on 7th April 2021
- 2021 mid-term review on 21st June 2021
- 2021 General Assembly & Steering Committee meeting on 22nd November 2021
- 2022 Close-out meeting on 26th August 2022

2.2. WP2: Well re-use and leakage assessment tool development

2.2.1. Objectives

The aim for this work package is to create a publicly available well screening-tool and a workflow that facilitate preliminary evaluation of the feasibility of using existing oil/gas wells as CO_2 storage wells.

WP2 has been divided into six tasks and the objectives for each of them together with a statement related to successful achievement or not are written in the tables below.

Task	Achievement
Task 2.1 Identify tool specifications including appropriate software platform, inputs and outputs, underlying technical approach for well assessment (LANL, TNO, IFPEN, SINTEF, GeoEcoMar, UKRI-BGS)	A set of requirements for the tool were identified through discussions with the project partners including industry partners. In addition preliminary design of tool was identified including inputs/outputs. The overall tool design was based on the NRAP-Open-IAM framework used by US DOE's NRAP project for its integrated assessment modeling tool and TNO's Bayes-I Well Tool framework.
Task 2.2 Develop technical approach for assessment of well re-use potential in collaboration with industry (TNO, LANL, GeoEcoMar, UKRI-BGS)	A technical approach was developed taking into consideration CO_2 storage well design and integrity requirements by referring to standards, guidelines, regulatory requirements and past industrial experiences. The approach was further refined through extensive consultations with well design and integrity experts from industry partners.
Task 2.3 Develop technical approach for assessment of CO_2 /brine leakage risk (SINTEF, LANL, TNO, GeoEcoMar)	A technical approach integrating LANL's leakage risk quantification work and TNO's cement mechanical integrity failure work was developed to quantify leakage risks through fractures at wellbore cement/caprock/steel interfaces. The approach was translated to develop models for risk quantification and incorporated as beta-version in the well screening tool.
Task 2.4 Develop the well screening-tool (LANL, TNO, GeoEcoMar)	A well screening tool was successfully developed using the technical approach for well screening.
Task 2.5 Demonstrate tool applicability with example data sets (TNO, GeoEcoMar)	Applicability of the tool was demonstrated using the P-18 well dataset. The tool was subsequently used for national case studies in Work Package 4.
Task 2.6 Update/improve tool for case study assessment (LANL, TNO, GeoEcoMar)	The lessons learned through application of the tool to national case studies was used to identify bugs in the tool as well as other issues to improve its functionality and usability. The tool was updated based on the feedback.

2.2.2. Main results

The results shown in the following for each task in WP2 are as summarized in the public guideline reports, i.e., D2.1, D2.2, D2.3, and D2.4

2.2.2.1. Task 2.1 Identify tool specifications including appropriate software platform, inputs and outputs, underlying technical approach for well assessment

A conceptual workflow for well screening was developed by taking into consideration the state-of-the-art on requirements of a CO_2 storage well design. The workflow was designed to assess a well's suitability based on its ability to maintain integrity under expected operational conditions (such as high pressures and corrosive environment) as well as to meet its desired operational purpose. The workflow included multiple steps for checking a well's integrity. It was decided that due to limitations in available funding as well as time the well screening tool will be developed around a qualitative screening approach rather than quantitative approach. This led to development of a decision tree based well screening design. The conceptual workflow was subsequently used to identify various inputs that will be required to perform well screening assessment including well-specific inputs (e.g. well design, well completions, information on well components, well tests) as well as field-specific inputs and expected operational conditions. We also decided that the screening outputs will be qualitative and designed a traffic light approach to convey screening results. We decided to base the tool's computational framework on the NRAP-Open-IAM tool (developed by US DOE's NRAP program) and Bayes-I Well Tool (developed by TNO) in order to take advantage of the combined experience by developers at LANL and TNO. The tool was coded using the Python programming language.

2.2.2.2. Task 2.2 Develop technical approach for assessment of well re-use potential in collaboration with industry

We performed extensive literature search to develop the technical approach underlying the well assessment. One of the challenges was that very little information is available in the public domain on the standard workflow used for assessing feasibility of using existing oil/gas wells for CO_2 storage. On the other hand, information on the steps taken to evaluate existing wells for the Peterhead/Goldeneye and Kingsnorth projects is publicly available. In addition, TNO has also worked on assessment of the P-18 well as part of the Porthos project. In order to develop an assessment framework we had to identify CO_2 storage well design requirements. We referred to the ISO 27914 standard which is focused on CCS wells as well as regulatory requirements such as those defined by US EPA's Class-VI well for CO_2 storage. Our well assessment was primarily focused on assessing integrity of the existing wells under expected conditions in a CO_2 storage reservoir. The assessment included five major steps, out-of-zone injection risks, integrity of primary well barrier, integrity of secondary well barrier, structural integrity and material compatibility. We developed decision trees specific to each of these steps which included step-by-step evaluation of various well components. The workflow and the decision trees were discussed in an internal REX-CO_2 workshop on 15 October 2020, in order for the partners to understand the framework underlying the queries asked during application of the tool. The workshop served as a session where the partners could provide feedback and suggestions on the decision trees. The workflow and decision trees were subsequently used to develop the well screening tool.

2.2.2.3. Task 2.3 Develop technical approach for assessment of CO_2 /brine leakage risk

We developed a quantitative approach for assessment of leakage risks. The approach included two steps, 1) estimate the probability of developing leakage pathways at the cement/caprock interface due to debonding of cement as well as the mean aperture of resulting micro-annuli, 2) utilize the mean aperture and storage reservoir pressure to estimate the time-dependent CO_2 leakage rate and cumulative leakage over the lifetime of the project. For both steps we utilized fast, predictive models developed using machine learning based approach. The models to estimate probability of cement failure were based on a set of 4000 geomechanical numerical simulations performed by TNO by sampling through four different uncertain parameters, including Young's modulus of cement, Poisson's ratio of cement, tensile strength of cement-rock interface, and injection temperature difference. The principal output of the geomechanical simulations was the aperture of micro-annuli that develop in case of cement failure. Outputs of the 4000 simulation runs and corresponding inputs of the 4 uncertain parameters were used to develop the machine learning based fast models that can be used to predict micro-annuli as a function of uncertain parameters. For predicting the CO_2 and brine leakage rates we utilized the reduced order model (ROMs) developed by LANL for predicting leakage of CO_2 and brine through cemented wellbores as part the National Risk Assessment Partnership (NRAP) project. The ROM takes as input the effective cement permeability, depth of storage reservoir and pressure and saturation in the storage reservoir and predicts the CO_2 leak rate. For this project, the predicted aperture of micro-annuli output from the geomechanical ROM was used to estimate an effective permeability for cement with the micro-annuli. Similar to the geomechanical ROM, the wellbore leakage ROM was developed using an extensive set of high-fidelity numerical simulations of CO_2 injection in a reservoir and its leakage through a cemented wellbore. Both the models were integrated in the screening tool to provide a user an ability to quantify leakage due to cement failure. Given that the geomechanical model was based on the P18 well design, we determined that the combined leakage model will have limited applicability only for the well designs and parameter ranges similar to P-18.

2.2.2.4. Task 2.4 Develop the well screening-tool

A well screening tool was successfully developed using the technical approach described in 2.2.2.2 and 2.2.2.3 and the computational framework discussed in 2.2.2.1. he functionality of well assessment tool has been checked and been confirmed through exercising the tool through a hypothetical well assessment. In addition, we also collected feedback from other project partners and updated the tool prior to sharing it with Work Package 4 team for its application to national case studies.

2.2.2.5. Task 2.5 Demonstrate tool applicability with example data sets

The initial, or *beta*, version of the REX-CO_2 tool was developed and distributed among the consortium members in November 2020. Both the WP2 and WP4 team members performed preliminary test runs of the tool. The objective was to have an initial interaction with the tool and its functionality and provide feedback on the functionality and usability of the tool.

On 14 December 2020, a feedback session was held with the WP4 team to gather their overall impression and feedback on usability of the tool through application to real data from national case studies. Through this workshop we were able to identify the primary issues encountered when using the tool and subsequently update the tool to address the core issues.

During this period the decision trees have also been continually updated taking into consideration the suggestions from the consortium partners. To facilitate the feedback cycle, a spreadsheet was developed to catalog and track the issues encountered while using the tool as well as other suggestions and comments. In preparation for the WP4 feedback session, the partners were asked to structure their feedback along the following points: general impressions, what works nicely, must-have updates, and nice-to-have updates. These were identified and further discussed during the online workshop. The feedback was used to update the tool and it was subsequently applied to national case studies.

2.2.2.6. Task 2.6 Update/improve tool for case study assessment

The results of application of the well screening tool to the national case studies is discussed in WP4 summary in Section 2.4. Following the national case studies, a workshop was held between the WP2 and WP4 team members to gather feedback on issues with the tool that should be fixed prior to its public release. The WP4 teams were asked to identify the issues using an online spreadsheet prior to the workshop. During the workshop discussions, the teams ranked the issues based on their severity including high, medium and low. It was decided that the high and medium ranked issues will be prioritized and fixed. The tool has been subsequently updated to fix the identified issues.

2.3. WP3: Experimental investigation for re-using wells for CO_2 storage

2.3.1. Objectives

To conduct an integrated laboratory and numerical modelling program to assist in the assessment of existing wells and to provide strategies for remediating well leakage. The program aims to define down hole boundary conditions at which well integrity could fail and/or be remediated.

WP3 is organized in four tasks addressing each objective outlined above; several ECCSEL-ERIC research facilities were used.

Task	Achievement
Task 3.1 Laboratory investigation of well and surroundings material properties (UKRI-BGS, IFPEN, SINTEF)	The effect of curing pressure and CO2 exposure on bond strength was examined. The use of Microbial induced calcite precipitation as a novel active remediation technique was tested.
Task 3.2 Laboratory determination of the state of stress of cement as placed in well environments (LANL, SINTEF)	State-of-stress experiments were performed for development and verification models
Task 3.3 Development of work-over and remediation technologies to enable well re-use (SINTEF, IFPEN, UKRI-BGS, TNO, LANL, Restone AS, Equinor)	Two different microbe systems were tested for their ability to induce calcite precipitation.
Task 3.4 Numerical simulation for upscaled analysis of well response to thermal and geomechanical stresses including self-sealing and the efficacy of remediation (IFPEN, SINTEF, TNO)	Models were further developed and tested against both field and laboratory data with good results.
Extra Task Deliver a report on material selection with state of the art relevant knowledge and information related to re-use of existing wells for CCS (Vallourec)	Impact of CO_2 on well completion and material selection for CCS storage operations.

2.3.2. Main results

The results shown in the following for each task in WP3 are as summarized in the public reports and publications, i.e., D3.1, D3.2, D3.3, D3.4, D3.5 and extra Deliverable D3.6.

2.3.2.1. Task 3.1 Laboratory investigation of well and surroundings material properties

This task focused on characterization of cement and cemented interfaces for the application of CO_2 storage. The contribution was divided into separate objectives.

The first objective was to capture the mechanical behavior of the interface. This was performed by performing tests on fresh cement interfaces in order to assess the effect of various parameters on the mechanical strength such as:

- What are the mechanical properties of the material at depth after x years?
- What is the effect of curing pressure?
- What is the effect of interface condition: roughness, drilling fluid presence, rust?
- What is the effect of cement-rock stiffness ratio on thermal cycling?

The testing was performed on two different stress configurations: push-out test, the pull-out test and cycling radial pressure tests. The push-out test would give a measure of the shear bond strength between the two materials, whereas the pull-out test would give the tensile bond strength between the two materials. The cemented interfaces were towards steel and/or sandstone and halite rocks. The cyclic radial pressure tests were performed on sandstone and cement samples of varying stiffness.

The secondary objective was to examine the effect of CO_2 aging on the interface mechanical strength. This was performed by studying how CO_2 permeation affects the mechanical strength towards shear resistance. Various exposure conditions were used such as saturated brine + CO_2 and supercritical dry CO_2 at 100 bar and 66 °C. These tests were also used with various interface conditions such as sound, mechanically failed and with the presence of drilling fluid.

The conclusion of these test was that the curing pressure increases the mechanical strength. This opens the possibility to assess the quality of the well from the knowledge of the environmental pressure during the drilling and completion of the well. A potential follow-up for these tests could be the further assess the residual state during the cement curing. The tests should also be compared with larger scale experiments.

The tests on halite-cement interface showed that there was no adhesion with a neat Portland G cement formulation. This is due to the dissolution of the free water coming from the cement slurry. With the effect of free water and dissolution of the salt the mechanical strength comes solely from salt creeping and compressive loading. A potential follow-up on this work would be to examine the halite-cement interface with an industrial cement formulation dedicated to salt formation.

The tests also showed that wellbore cement is likely to have reacted with the formation fluids, and so this may lead to changes in the mechanical properties by promoting crystallization of cement microstructure.

2.3.2.2. Task 3.3 Development of work-over and remediation technologies to enable well re-use

The development of work-over and remediation technologies tested various methods and measures to enable well-use. The objectives of this task were as follows:

- Could microbial induced calcite precipitation modify the properties of the cement-rock interface?
- Can manipulation of the local effective stress field through pore fluid pressure regulation deform caprock or cement and reduce the fracture/microannuli?

The first step in the workflow to study the effect of Microbial induced calcite precipitation was to identify the initial properties of the system geomaterials. This was performed by mapping the mechanical behavior of the materials in their initial state. Two isolates were selected after a screening process and were utilized in flow experiments by inoculating cement sandstone samples. The experimental work showed that microbial induced calcite precipitation is possible, however, the concept still needs to be further tested and analyzed before this can be used as a remediation solution.

Experiments using a scaled down well system in a triaxial apparatus for cement damage and flow properties examined the cement-casing microannuli properties. The tests on the manipulation of casing-cement microannuli by controlling the casing pressure showed that there were no permanent effects on the aperture due to well pressure variations.

2.3.2.3. Task 3.4 Numerical simulation for upscaled analysis of well response to thermal and geomechanical stresses including self-sealing and the efficacy of remediation

The work on the upscaling examined the creation of radial cracks in the cement sheath and the rock formation. A Modified Discrete Element Method (MDEM) was calibrated with the experimental results of both low and high confining pressure and used to further model the effect of standoff, boundary stress conditions and the effect of sandstone and shale rock types. The results showed that for a given casing pressure, the number of cracks as well as their size is less affected by the casing standoff between 50 – 100 %. The modeling also confirmed the experimental data that crack creation and propagation is a function of the rock stiffness. The effect of the boundary stress showed that the higher the boundary stress, fewer cracks were created at a given casing pressure.

The numerical work on predicting the cement-sheath integrity utilized a model that accounted for the cement sheath initial state of stress *and* the transient thermoporoelastic effects. The safe operating pressures and temperatures where then predict to simulate where cement sheath could exhibit failure. The model predicted the safe operating envelope for shear, tensile, and debonding cement sheath failures caused by pressure and temperature perturbation after the cement has set. The model also predicted that the pore pressure is a key factor for cement failure, particularly for rapid temperature changes. If the formation has low permeability, the transient pore pressure are amplified which in turn increases the risk of damage. Compared with conventional thermoelastic models, the thermoporoelastic model predicts a smaller safe operating envelope when heating the internal casing fluid, and a larger envelope when cooling the internal casing fluid. The heating rate was considered with respect to field applications and slower heating/cooling rates can prevent damage to the cement sheath. The model was also applied to explain several laboratory and field experiments and achieved good results.

2.3.2.4. Extra Task Material Selection for CCS

The aim of the extra deliverable report is to describe conditions expected in antriopogenic CO_2 injection wells and to provide recommendations for material selection of CCS storage wells. There are no industry standards for material testing and selection in the CCS environment, thus Vallourec delivered a report based on their long experience and research in testing materials for the oil and gas industry and CO_2 environments.

The main challenge in selecting adequate materials for CCS projects depends on the impurities present in the CO_2 stream and increased risk of extremely low temperatures due to depressurization. Well materials must sustain the lowest expected temperature in case of depressurization as the steel may become brittle increasing the risk of failure and crack propagation. In general, the use of 13Cr material is not recommended in case of low temperature or the presence of impurities. Super Duplex material solution anneal are optimal choice in presence of dense CO_2 and large variety of impurities. They present higher toughness resistance at low temperature than cold worked super Duplex. Super 13Cr material may be a cost effective solution for CO_2 stream with limited impurities.

With their expert knowledge, Vallourec contributed to updating the decision tree of the well screening tool for material compatibility.

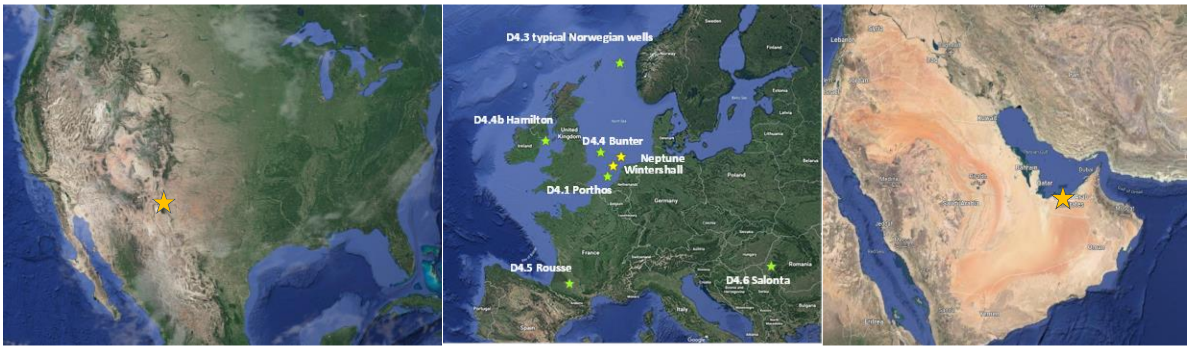
2.4. WP4: National well re-use case studies

2.4.1. Objectives

The principal aim of this WP is to provide a detailed evaluation of activities required to ensure safe and economic CO_2 storage in the selected fields by identifying well integrity issues of well candidates using the REX-CO_2 well screening tool. Therefore, in collaboration with the industry partners in the project, case studies were selected in each of the participating countries. The selected case studies are used to perform national re-use assessments with the REX-CO_2 tool that has been developed as part of Work Package 2. These will serve to validate the screening framework and contribute to re-use procedures tailored to specific well designs across the portfolio of different sites. The tool was applied in both on- and offshore wells, with different applications (CCS and CO_2-EOR), varying depths between 1400-5000m, reservoir rock (sandstone and carbonate), and type (gas field, oil field and saline aquifer), capacity and number of available wells.

In total 10 case studies across 7 countries allocated in 3 continents (North America, Europe and Asia) created a portfolio of 60 wells which were assessed with the REX-CO_2 screening tool. The national case studies with corresponding number of wells are as follows:

- The Netherlands: Porthos (5), Wintershall (6), Neptune (2)
- US (4)
- Norway (3)
- UK: Bunter Sandstone Saline aquifer (12), East Irish Sea Gas Fields (4)
- France (1)
- Romania (12)
- UAE (6)



Location of case studies (Google Maps)

Each case study was part of a dedicated task where results have been published in form of a deliverable report available for download at the official project website. The table below summarize these tasks and main achievements.

Task	Achievement
Task 4.1 Re-use assessment of a gas field in the Netherlands (TNO, IRO, EBN)	A verification case study with result being in-line with expert assessment of candidate wells in the offshore gas reservoir intended for CCS.
Task 4.2 Re-use assessment of potential candidate wells in USA (LANL, Chevron)	Well re-use potential of a typical US oil field currently used as a CO_2-EOR site.

Task 4.3 Re-use assessment of a potential CO_2 storage site in Norway (SINTEF, Equinor)	Re-use potential of typical oil and gas production wells in the Norwegian Continental Shelf.
Task 4.4 Re-use assessment of a potential CO_2 storage site in the UK (UKRI-BGS, IKON)	Well re-use assessment of a saline aquifer site, identifying key issues and potential benefits for re-using existing wells for CO_2 storage in saline aquifers
Task 4.5 Re-use assessment of a potential CO_2 storage site in France (IFPEN)	A verification case study based on the conducted CCS project in the Rousse field. Screening results aligned with workover requirements prior to the CO_2 injection.
Task 4.6 Re-use assessment of a potential CO_2 storage site in Romania (GeoEcoMar, TNO)	Well re-use assessment of a depleted abandoned gas reservoir in western Romania
Extra task: Re-use assessment of a potential CO_2 storage site in UK (UKRI-BGS)	Identification of key issues and potential options for re-using existing wells in UK depleted gas field settings
Extra task: Re-use assessment of a potential CO_2 storage site in the Netherlands (TNO, Neptune)	Well re-use assessment of existing wells in an offshore depleted gas field in the Dutch North sea.
Extra task: Re-use assessment of a potential CO_2 storage site in the Netherlands (Wintershall, TNO)	Testing and validation of the tool, identification of data gaps, and establish a ranking of candidate wells for CO_2 storage in the Dutch North sea depleted gas reservoir.
Extra task: Re-use assessment of a potential CO_2 storage site in United Arab Emirates (TNO, ADNOC)	Identification of well integrity issues and re-use potential of existing wells typical for the Gulf region in the Middle East.

2.4.2. Main results

The results shown in the following for each task in WP4 are as summarized in the public Case Study reports, i.e., D4.1, D4.2, D4.3, D4.4, D4.4b, D4.5, D4.6, and D4.7

2.4.2.1. Task 4.1 Re-use assessment of a depleted gas field in the Netherlands

The case study focused on re-use potential of five candidate wells for CO_2 injection in the Porthos field, and served as a verification case study by comparing results with the outcomes of published technical feasibility of the field (Neele et al., 2019). The screening approach was twofold by first screening the wells in the current state and then again with the assumed workover.

The screening results identify well integrity issues that were also highlighted in the experts evaluation and show that severe remediation could be expected for all wells. Most common issues are related to the poor quality or missing cement bond, repositioning of the production packer, unknown corrosion status and overall recompletion of currently unsuitable production equipment. However, the workover scenario proved that if all workover requirements are properly addressed wells can be fit for safe storage operations. The screening framework provides systematic approach to evaluate the current state and re-use potential of the wells in a consistent manner and enables the possibility to create different screening scenarios for the same well.

2.4.2.2. Task 4.2 Re-use assessment of potential candidate wells in USA

The US case study is focused on the Vacuum Field, which is an on-going CO_2 Enhanced Oil

Recovery (CO_2 -EOR) operation and is not considered as a CO_2 storage site. Therefore, the case study was purely used for demonstration purposes to demonstrate the CCS potential of a typical oil well in the USA by evaluating re-use potential of nine wells with the REX-CO_2 tool. Common integrity issues were related to corrosion, material incompatibility and potential leakage along the primary and secondary barrier. All the well-specific details were obtained from information available in the public domain, and thus certain screening categories lacked some data to conduct full assessment.

The overall conclusion is that the US case study demonstrates that the REX-CO_2 tool can be applied to a typical oil-field site in the US to identify integrity issues in a consistent manner. The tool has great potential to be utilized in well re-use potential assessment in some ongoing U.S. carbon storage projects (e.g., CarbonSAFE-San Juan Basin project) where a lot of existing wells will be evaluated before any potential re-use.

2.4.2.3. Task 4.3 Re-use assessment of a potential CO_2 storage site in Norway

The objective of the Norwegian case study in REX-CO_2 WP4 is to examine the re-use potential for typical production wells of the Norwegian Continental Shale (NCS). Three wells have been selected by Equinor to represent wells with construction details, well path geometries, age, and availability of documentation that could be encountered when investigating the potential of well re-use for CO_2 injection into a depleted oil or gas field. The oil and gas fields that the three selected wells produce from are not currently being considered for CO_2 storage, but rather serve to test and validate the applicability of the screening tool on a typical NCS wells if used for CCS purposes.

The screening indicated a potential need for extensive workover for all three wells to make them suitable for re-use as CO_2 injection wells. The main issues were related to the unknown state of cement and/or degree of corrosion on casings, material incompatibility and unknown status of the structural components. Besides workover and data collection requirements, the conclusion is that the tool provides a systematic approach in identifying potential integrity issues and enables the well operator to look for well information required to complete full engineering assessment.

2.4.2.4. Task 4.4 Re-use assessment of a potential CO_2 storage site in the UK

The UK case study evaluated the well re-use potential at a saline aquifer site known as Bunter Closure 36. Suspended gas production wells at the site are designed to produce gas from a gas field underlying the saline aquifer structure, and therefore do not permit access to the saline aquifer CO_2 storage target. Accessing the reservoir would therefore involve permanently plugging the well beneath, and some combination of cutting and pulling production casing, or milling extensive cemented casing intervals prior to perforation. The number of cemented casing intervals over the saline aquifer interval may provide a preliminary screening criterion.

A key issue identified is that the casing materials over the saline aquifer interval do not conform to the recommended specification to ensure resistance to corrosion. The flow-wetted section beneath any new packer installation will therefore be subject to corrosion, which may be significant. There may be potential to re-use some of the wells penetrating the Bunter Sandstone to monitor the performance of the wider saline aquifer system. There is significant uncertainty regarding the properties of the formation and its hydraulic connectivity. A far-field monitoring well could provide valuable information that could validate model performance and provide confidence to stakeholders. Far-field wells would neither be subjected to CO_2 -rich fluids, nor affected by thermal responses to injection. Consequently, such wells do not present a CO_2 leakage risk and there are fewer material compatibility considerations.

2.4.2.5. Task 4.5 Re-use assessment of a potential CO_2 storage site in France

The French case study was based on the pilot CO_2 storage project that was performed in the Mano formation of the Rousse gas field between 2010 and 2013. It served as the only validation case in the REX-CO_2 project that was based on the actual field project, and thus provided valuable insight into the application of the tool to assess re-use potential of candidate wells. The field contains three wells, but only one (RSE-1) that penetrates the caprock and has an access to the indented injection reservoir. Prior to the commissioning, the well was subjected to the workover to make it suitable for the CO_2 injection.

Well RSE-1 was screened with the REX-CO_2 tool and results showed no integrity issues, which makes the only well screened during the project to make it suitable for the CCS operation in the current state. This make sense as the well was subjected to the workover, but validates the framework of the tool to identify potential integrity issues in case there are any.

2.4.2.6. Task 4.6 Re-use assessment of a potential CO_2 storage site in Romania

The Romanian case study evaluated the well re-use potential at a depleted gas field named Salonta. Salonta field is located in the western part of Romania, within the Pannonian Basin, with hydrocarbon reservoirs in the sandstones from Lower Pliocene and in the fissured altered basement. The only suitable CO_2 storage reservoir was found to be the sandy horizon from Lower Pliocene from which gas was extracted. This reservoir has good properties but was exploited only through 2 wells (based on the received documentation), the primary productive horizon being considered the fissured/altered basement (at a greater depth than the Lower Pliocene reservoir).

This is a special case study since it involved the re-use assessment of old abandoned wells. A major issue when assessing this study was lack of data availability. Although the data for the 17 wells was provided by the regulator (NAMR), some of the data required by the REX-CO_2 tool was unavailable. Of 17 wells, only 12 were analyzed. 5 were excluded from the analysis due to the fact that the well files did not include sufficient data for running the tool.

It is worth mentioning that no CCS project is currently associated with Salonta, nor plans for future CO_2 storage exist. The case study is used as an example of a potential re-use of abandoned hydrocarbon wells from the western part of Romania, drilled in the 1980's.

The first conclusion of the study was that the wells cannot be re-used without significant intervention and that more data should be gathered to ensure at least their structural integrity.

After using the tool for assessing re-use potential of existing abandoned wells in future storage operations, we can conclude that there is a lot of potential for using the tool for the Romanian fields. Romanian fields have usually a large number of wells and the tool could be used in order to make a preliminary selection of the wells that could be considered for re-use.

2.4.2.7. Extra task: 4.4b Re-use assessment of a potential CO_2 storage site in the UK (east Irish Sea Gas Fields)

An additional UK case study was evaluated using the screening tool. The case study evaluated wells from the Hamilton Gas Field, as representative of wells in depleted gas fields in the East Irish Sea Basin. No significant issues were identified; however, casing steel specifications will necessitate consideration in risk management strategies.

2.4.2.8. Extra task: 4.7 Re-use assessment of a potential CO_2 storage site in the Netherlands (Wintershall Dea case study)

The principal aim of this case study was to test and validate the tool, identify data gaps, and establish a ranking of candidate wells for CO_2 storage in a depleted Soutern North Sea gas field. Targeted reservoir consists of several gas bearing formations in the Buntsandstein

Group with six wells selected based on the availability of the data and status of wells. The screening was done separately by Wintershall Dea and TNO comparing outcomes of selected wells to gauge the differences in applied criteria and to assess the tool's resilience to subjective approach in data interpretation.

The conclusions from both Wintershall Dea and TNO are that the screened wells would require significant interventions but could be good candidates for re-purposing as CO_2 injectors provided missing information is gathered, WBEs evaluated and verified and remediations carried out if and where necessary. Besides well integrity observations, the tool results are highly dependent on quality and accessibility of well data, and are subjected to individual interpretation of data, but user friendly interface allows for fast and consistent screening to rank CO_2 injector well candidates and its further engineering requirements.

2.4.2.9. Extra task: 4.8 Re-use assessment of a potential CO_2 storage site in the Netherlands (Neptune case study)

The Neptune Energy case study is focused on a potential use of a depleted gas field in the Dutch North sea with two candidate wells, screened with the REX-CO_2 tool as potential injectors. The screening was conducted independently by Neptune Energy and TNO with similar results.

The only difference in screening was due to different interpretation of certain questions in the well integrity primary and secondary barrier screening categories. Both parties concluded that wells cannot be used in the current state, but will require a severe remediation to potentially used them as injectors. Other observations conclude that the tool enables structured way to screen the wells in its current state, indicate information required to assess the integrity of candidate wells and helps in prioritizing wells in CCS field development.

2.4.2.10. Extra task: 4.9 Re-use assessment of a potential CO_2 storage site in United Arab Emirates (ADNOC case study)

The ADNOC case study is focused on the evaluation of oil and water wells in the Abu Dhabi region for the potential CCS applications. In total six wells have been screen with preliminary results showing that all wells could be used as CO_2 injectors if adequate interventions are considered.

2.4.3. Overall conclusions

Evaluation of 60 wells across 10 case studies yielded valuable insights into the tool value and showcased that the tool can be applied to any well design, regardless of its current status and reservoir conditions. Two case studies served as tool validation; the Porthos and French case study. The tool outcomes have been in line with the expert evaluation and matched the remediation requirements in case there were any. Overall, all case studies showed the potential to be used for CCS operation, as long as identified remediation requirements are properly addressed and/or additional missing data is acquired. The most common and relevant conclusions drafted from these case studies are as follows:

- The tool can be applied to any accessible well that is not abandoned
- The tool is user friendly with simple graphical user interface (GUI) which allows users to quickly get acquainted with the tool and it's easy to use.
- Framework allows for fast and consistent well screening, especially with large stock of wells to preliminary identify potential integrity issues.
- Value of the tool is in initial screening, and as a to-do list for the operators when it comes to data collection and interventions required.
- Qualitative approach aids in preliminary selection of candidate wells in early CCS project phase development, but does not replace a full engineering assessment.

- Data quality and availability drives the screening assessment and framework may result in subjective interpretation of data, and thus the screening outcomes.
- Results presented in a color coding approach enable decision makers to rank candidate wells based on the severity of interventions required.
- Most wells in its current state will require workover. The most common issues are related to incompatible completion, unknown corrosion status, unknown structural integrity when subjected to new expected loads, and in some cases status of the cement sheath. Workover opportunity to gather new data (logs).

2.5. WP5: Recommendations for re-using existing wells for CO_2 storage

2.5.1. Objectives

The principal aim of this WP is to develop technical recommendations for well re-use by combining the knowledge and lessons learnt from WPs 2–4. The provision of these recommendations will provide a reference document for both operators and relevant regulatory authorities, promoting the safe re-use of wells in accordance with current technical best practice.

Task	Achievement
Task 5.1 Summarised state of the art findings and recommendations based on underlying technical approach developed in REX-CO_2 (UKRI-BGS, LANL, TNO, GeoEcoMar)	Milestone report submitted to ACT
Task 5.2 Evaluation of experimental results in the context of developing recommendations for well re-use (UKRI-BGS, SINTEF, LANL, IFPEN)	Milestone report submitted to ACT
Task 5.3 Lessons learned from well re-use case study assessments (UKRI-BGS, TNO, LANL, SINTEF, IFPEN, GeoEcoMar)	Milestone report submitted to ACT
Task 5.4 Recommendations for re-using existing wells for CO_2 storage operations (UKRI-BGS, TNO, GeoEcoMar)	Deliverable 5.1 submitted to ACT and published online. The report provides the first document dedicated to providing recommendations for re-using existing wells for CO_2 storage.

2.5.2. Main results

The results shown in the following for each task in WP5 are as summarized in the public integrated recommendation report D5.1

2.5.2.1. Task 5.1 Summarised state of the art findings and recommendations based on underlying technical approach developed in REX-CO_2

Task 5.1 involved close collaboration with the REX-CO_2 tool development team from WP2. A written milestone report was prepared summarizing the rationale and recommendations underlying the screening process integrated within the tool. Whilst the milestone report was not published openly, the content of the report provided draft text that was later incorporated into the D5.1 Deliverable report.

2.5.2.2. Task 5.2 Evaluation of experimental results in the context of developing recommendations for well re-use

Task 5.2 involved close collaboration with the REX-CO_2 experimental team from WP3. A written milestone report was prepared summarizing the key findings, implications and resultant recommendations from the experimental programme. Whilst the milestone report was not published openly, the content of the report provided draft text that was later incorporated into the D5.1 Deliverable report.

2.5.2.3. Task 5.3 Lessons learned from well re-use case study assessments

Task 5.3 involved close collaboration with the technical team engaged in conducting the REX-CO_2 case studies in WP4. A written milestone report was prepared summarizing the key findings, implications and resultant recommendations from the case study programme. Whilst the milestone report was not published openly, the content of the report provided draft text that was later incorporated into the D5.1 Deliverable report.

2.5.2.4. Task 5.4 Recommendations for re-using existing wells for CO_2 storage operations

Within Task 5.4, the Deliverable D5.1 report was produced to provide 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.

Recommendations outlined 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.

2.6. WP6: Legal, environmental and social aspects

2.6.1. Objectives

This WP is aimed to evaluate the non-technical aspects that influence the implementation of well re-use application, from regulatory (legal) aspects to public acceptance.

Task	Achievement
Task 6.1 Assessment of environmental and legal framework in participating countries (GeoEcoMar, TNO, SINTEF, LANL, Restone, UKRI-BGS, CO_2 Club, IFPEN)	Deliverable D6.1. available online summarizes the data collection process and initial results. D6.1. presents the current regulatory framework for well re-use in the participating countries. Deliverable D6.2. available online. D6.2. summarizes the results of the comparative analysis made on the existing regulations for well re-use in REX-CO_2 countries. Milestone MS4. Data collection on regulatory frameworks in participating countries Milestone MS7. Workshop with stakeholders
Task 6.2 Recommendations for a coherent legal and environmental framework and guidelines for permitting process (GeoEcoMar, TNO, SINTEF, Restone AS, CO_2 Club, IFPEN, UKRI-BGS)	Deliverable D6.3. available online. D6.3. presents the first set of recommendations made for improvement of current legislation for enabling well re-use. Deliverable D.6.4. available online. D6.4. presents the final recommendations for improvement of regulatory framework for well re-use based on a review of the first set with industry partners and regulators. Milestone MS14. Identification of gaps in the national legislation for well re-use
Task 6.3 Public and stakeholder perception and acceptance (TNO, GeoEcoMar, SINTEF, LANL, Restone, UKRI-BGS, CO_2 Club, IFPEN)	Deliverable D6.5. available online. D6.5. presents the first survey on stakeholder and public acceptance of well re-use. Deliverable D6.6. available online. D6.6. illustrates the premises and the structure aof a public communication strategy for well re-use. Milestone MS9. Implementation of public surveys

2.6.2. Main results

The results shown in the following for each task in WP6 are summarized in the public reports, i.e., D6.1, D6.2, D6.3, D6.4, D6.5 and D6.6.

2.6.2.1. Task 6.1 Assessment of environmental and legal framework in participating countries

Task 6.1. focused on assessing the existing regulatory frameworks for well re-use in the participating countries of REX-CO_2 (D6.1.), based on collection of publicly available data and discussions with stakeholders (mostly regulators and industry) and on identifying the gaps in the current legislation as a result of the comparative analysis presented in D6.2. The findings were checked and discussed within a workshop with stakeholders organized on an online platform on 10th of February 2021.

The main conclusion that was drawn from this work was that little has been specifically regulated for well re-use in the participating countries, although there are regulations for CO_2 geological storage (CCS Directive in Europe and Underground Injection Control program in US).

The potential gaps identified in the current legislation refer to transition from hydrocarbon production to storage (procedure for postponing decommissioning wells, simultaneous hydrocarbon production and CO_2 storage), hibernation of wells (rules for mothballing and hibernation of wells, ownership of wells and costs), permitting well re-use (rules for permitting monitoring and testing), policy for well re-use (promoting well re-use and incentivization).

2.6.2.2. Task 6.2 Recommendations for a coherent legal and environmental framework and guidelines for permitting process

Task 6.2. built on the results of task 6.1, having as main objective to formulate recommendations for improvement of current regulatory framework to enable well re-use. The first recommendations presented in deliverable D6.3. were made based on the identified gaps found within Task 6.1. The key issues found based on the gap analysis were: postponing decommissioning of a well for a sufficient period of time to allow potential re-use for CO_2 storage; requirements to consider re-use in the decommissioning plans; liability during hibernation time, removing the risk for the hydrocarbon operator, long term liability, procedures/recommendations for converting a well for CO_2 storage and incentives to re-use existing wells for CO_2 storage.

The first recommendations were reviewed together with industry partners within a dedicated workshop held in January 2022. The revised and final recommendations were formulated following this workshop and presented in deliverable D6.4. These final recommendations are:

- Regulators should have a strategic overview of the most suitable sites
- Governments should support more open access of well data
- Assessment is needed by operator for re-use prior to decommissioning
- Postponing decommissioning should be accommodated to allow for re-use

These recommendations were also presented to regulators within a joint workshop with WP2 and WP4 in March 2022.

2.6.2.3. Task 6.3 Public and stakeholder perception and acceptance

In this task, WP6 partners of REX-CO_2 have assessed stakeholder and public perception and acceptance relating to re-use of wells for CO_2 storage in the participating countries. For the assessment of stakeholder and public perceptions and acceptance related with well re-use in CO_2 storage operations, a publicly available questionnaire was designed and made available through the REX-CO_2 website.

The survey reached 333 respondents covering all 6 countries represented in the REX-CO_2 consortium and a few respondents from other countries. Although this is not extensive enough to reach conclusions on public perception on well re-use, it provides an initial insight from stakeholders on which benefits could potentially be utilized in communication strategies.

The results of this first survey, presented in deliverable D6.5., are encouraging. The general attitude towards the idea of well re-use in CO_2 storage operations was positive. This re-use was considered to be an important factor for the general opinion on CCS both by respondents with in-depth knowledge and with limited knowledge.

The survey was also analyzed at a national level. Overall, the trends of the entire survey are also seen at a national level. Some minor deviations were recorded and emphasized through the comments received. The concerns addressed by the respondents refer to ability of depleted hydrocarbon reservoirs to permanently store CO_2 (highlighted from respondents in France), risk of leakage (respondents in the Netherlands), potential unsuitability of old wells in CO_2 injection operations (respondents in Romania). Some respondents also raised the concern that CCS as a technology can mean maintaining the current emission intensive technologies and an opportunity to produce more emissions.

Based on the results of the survey and on an extensive literature overview, a briefing document for future communication experts was elaborated as basis for communication strategies for future projects involving well re-use for CO_2 injection/storage (deliverable D6.6.).

The future communication strategy should be based on the following points:

- 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).

2.7. WP7: Dissemination and communication

2.7.1. Objectives

The principal objective of the dissemination and communication WP is to establish an effective communication within the consortium, including associated partners, and to disseminate project information and results.

Task	Achievement
Task 7.1 Website and social media (TNO)	The website was created and regularly used by both consortium members and the public. Twitter and LinkedIn accounts were also regularly used.
Task 7.2 Communication plan (SINTEF, TNO)	A communication plan was established at the start of the project and used throughout to ensure the effective communication of project results.
Task 7.3 Newsletter (CO_2 Club & TNO, all)	A total of 4 newsletters were published with approximately 100 downloads each.
Task 7.4 Knowledge dissemination and international collaboration (GeoEcoMar, all)	All results have been shared in public webinars and regularly at international conferences. Peer review papers have also been published.

2.7.2. Main results

The results shown in the following for each task in WP7 are as summarized in the public report and newsletters, i.e., D7.1, D7.2, D7.3 and D7.4

2.7.2.1. Task 7.1 Website and social media

For the REX-CO_2 project a dedicated project website was created (https://rex-CO2.eu/index.html) which provided an overview of the project and consortium members and has access to all publicly available deliverables. Regular news items were also posted and a contact page was provided.

All the reports are now available to download (https://rex-CO2.eu/downloads.html) and a summary of downloads to date is provided in Figure 2.

ID	Title	Count
D2.1	Current state-of-the-art assessments and technical approach for assessment of well re-use potential	272
D2.2	Summary report of well assessment tool framework	211
D2.3	Report on the REX-CO2 well screening tool	226
D2.4	Report on well assessment tool demonstration results and updates	95
D3.1	Cross-experimental methodologies and background results for assessing complex borehole conditions	137
D3.5	Conference paper on upscaling simulations	7
D4.1	Re-use assessment of a potential CO2 storage site in the Netherlands: Porthos	75
D4.2	Re-use assessment of a potential CO2 storage site in the USA: the Vacuum Field	44
D4.3	Re-use assessment of a potential CO2 storage site in Norway	3
D4.4.1	Re-use assessment of a potential CO2 storage site in the UK: Bunter Sandstone	57
D5.1	Recommendations for re-using existing wells for CO2 storage	4
D4.4.2	Re-use assessment of a potential CO2 storage site in the UK: Irish Sea	12
D4.5	Re-use assessment of a potential CO2 storage site in France: the Rousse Case	8
D4.6	Re-use assessment of a potential CO2 storage site in Romania	10
D4.7	Re-use assessment of a potential CO2 storage site: Wintershall Dea Case Study	10
D6.1	Report on the assessment of policy, legal and environmental framework	126
D6.2	Comparative analysis of regulatory frameworks	54
D6.3	Recommendations for Improvement of Legal and Environmental Framework	8
D6.4	Guidance for Mitigating Potential Regulatory Barriers	17
D6.5	Assessment of stakeholder and public perception of well re-use for CO2 storage	47
D6.6	Public communication strategy for future projects involving well re-use for CO2 injection/storage	35
D7.4	REX-CO2 Newsletter from the Second Year	89
D7.3	REX-CO2 Newsletter from the First Year	76
D7.2	REX-CO2 Kickoff Newsletter	111

Figure 3 Overview of deliverables available on project website and number of downloads as of the 8th August 2022.

A Twitter and LinkedIn account were also created for the project. The LinkedIn account was more popular, with 560 followers, this jumped dramatically after the recent joining of ADNOC who also shared the page on their social media. This created 413 new followers. In the 7 day period following ADNOC joining in August 300 people visited the REX LinkedIn page.

The Twitter account has 180 followers and the last tweet on the account, announcing ADNOC joining received 2916 views.

Given the very specific technical content of REX-CO_2 the social media accounts received the expected amount of interaction.

2.7.2.2. Task 7.2 Communication plan

A communication plan was produced at the onset of the REX-CO_2 project. This plan consisted of four targeted dissemination levels:

Level 1 – EC/ERA-ACT communication	Periodic financial and technical reporting; contact with EU project officer and/or national funding agencies on demand
Level 2 – Project management communication	Key notes of MB and SC meetings
Level 3 – Communication on WP and task level	Use of internal project website, exchange of knowledge and collaboration by meetings, email, reports and/or presentations
Level 4 – Communication between scientists	Day-to-day communication on task and subtask level, if required with WP leads by conference calls or email
Level 5 – External communication	Project website, publications, dissemination activities as described in WP7

Figure 4 REX-CO_2 dissemination levels as highlighted in the communication plan.

The communication within REX stayed along this plan and all levels were reached as described.

2.7.2.3. Task 7.3 Newsletter

Three newsletters were produced as described in the project proposal. A kick-off newsletter and then a year 1 and year 2 update newsletter. No newsletter was planned for closing the project but one will be produced in September 2022 to close the project and summarize each work packages findings.

Each newsletter was downloaded about 80-100 times off the website, but was also shared on social media.

2.7.2.4. Task 7.4 Knowledge dissemination and international collaboration

Knowledge dissemination occurred throughout the project, both in small technical invitation only groups, and large public webinars.

Project results will also be shared in September at the SPE well integrity conference in the Netherlands and in October 2022 at the GHGT-16 conference in France.

3. Project impact

The ambition of ACT is to facilitate the emergence of CCUS via transnational funding aimed at accelerating and maturing CCUS technology through targeted innovation and research activities. The importance of implementing CCUS (and even accelerating) has been accepted by the global community and is seen as a key method of greenhouse gas removal and delivering net zero emissions, which is critical to meet climate goals of the Paris Agreement.

The REX-CO_2 project links to this ambition by evaluating the feasibility of re-purposing oil and gas infrastructure (that have reached the end of their commercial life) as part of new Carbon Capture and Storage (CCS) infrastructure networks. The REX-CO_2 direct project impact is in providing standard approaches and a publicly available tool to aid in this evaluation, something that is not available elsewhere.

At project completion, REX-CO_2 has established an effective platform for E&P Operators, Regulators, Government Institutions, Service Providers, Consulting partners to interact in a non-competitive environment.

3.1. Key achievements

The REX-CO_2 project has been the first project to develop a publicly available Well Integrity Screening Tool to assist decision-makers with a systematic and auditable approach for re-use assessment of existing oil and gas wells for CO_2 storage. Based on industry feedback and the significant interest raised among external parties, the Tool can be particularly valuable in the early phases of the Opportunity Realisation Process (the Assess & Select phase), by providing a fast indication which wells are best candidates for re-use and what remediation would be required.

The experimental and laboratory scope of the project has delivered the required resources (e.g. existing datasets and models) to be able to give feedback whether the historic use of a well have led to increasing risk of compromised well integrity. This is important to be able to assess whether a well can/should be re-used or not.

Evaluation of the large portfolio of wells in the international case studies showed that the current tool can be applied to any well design regardless of the location and reservoir conditions as long as the well is accessible and not abandoned. The systematic framework enables ranking of candidate wells based on their well integrity status and ensures fast and consistent approach to screen wells consistently. Outcomes of the tool are validated and in line with expert assessments in validation case studies. The tool allows for a significant reduction of the manhours spent on well by well analysis and thereby facilitates accelerated decision making, and decreasing the overall costs of maturing a future CO_2 storage site.

With the delivery of the D5.1 “Recommendations for re-using existing wells for CO_2 storage” report, a framework of both technical and non-technical (legal & regulatory) considerations have been described. The evaluated regulatory frameworks have been fed into the logic of the Well Screening Tool decision trees, in order to relate the project recommendations to future storage license applications. The D5.1 document is intended to provide a foundational knowledge-base for well re-use, which can be used as initial recommendations for future guideline development. With this, we have defined the building blocks and initiated the dialogue that need to happen between oil & gas operators, regulators and future CO_2 storage site operator to avoid unnecessary decommissioning.

3.2. Knowledge gain

One of the aims of ACT is to promote industry involvement in projects like REX-CO_2 and increasing the TRL of CCUS technologies from the end-user perspective. The TRL of REX-

CO_2 at project closure should be separated into 2 different categories, with the development of the Well Screening Tool being more mature and having reached a higher TRL (e.g.TRL-6) as the experimental work (e.g.TRL-4). The industry partners confirmed the project has indeed achieved these TRL levels at the project close-out meeting.

The project contributed actively to CCS knowledge transfer between the consortium organisations across Europe, USA, and the Middle East and reaching out beyond the project boundaries to educate or inform interested parties.

3.3. Potential cost benefits

It is expected that substantial cost savings may be achieved by re-using existing oil and gas wells for CO_2 injection compared to drilling new wells. However, re-using existing wells come with higher uncertainty on their current integrity status and therefore potentially higher risks associated with the re-use operation and its future lifetime as a CO_2 injector. Generally, wells in their current state are likely not suitable to be used directly as CO_2 injectors, and a certain degree of remediation can be expected to make them fit for injection. A scenario of drilling new wells seems to reduce risks, but on the other hand, the leakage risk across the storage complex increases by additionally penetrating the caprock with these new wells. Furthermore, risks and costs increase as the existing wells will have to be abandoned.

The cost benefit analysis of re-using wells depends on many aspects, e.g. current state of the well, onshore/offshore, depth of the storage reservoir, well design, and thus would have to be considered on a well-by-well or field-by-field basis. The costs associated with remediation will most likely be lower than drilling new wells, and it is fair to consider that the re-use of existing wells is feasible in case risks associated with remediation are lower or the same as for drilling new wells.

4. Collaboration

The REX-CO_2 project is carried out by a strong performance consortium of partners that complement each other and strive to excel. The consortium has been put together to cover a wide range of expertise, interest, (research) experience and has partners contributing as industrial end-users. The accession of parties to the consortium mid-to-late-project has led to additional insights, extra deliverables and strengthened internal collaboration.

4.1. Transnational collaboration

The geographical spread of the participating organisations in the REX-CO_2 Consortium is spanning across 7 different countries, 3 different continents and 5 different time zones. Workshops, management board meetings and WP-meetings were therefore scheduled in the CET afternoons, to allow for as much as possible time overlap for communication and collaboration. This proved to be a very effective approach and the transnational time zone challenge was easily overcome.

The leadership and coordination of the various work packages was distributed among the consortium partners. All participants were committed to collaborate and considering the project was almost fully online, communication, engagement and responsiveness of partners was excellent. Almost all partners actively participated in the various WP-monthly meetings, and were engaged in discussion during these meetings, but also during the workshops and other milestone presentations.

The 9 international Case Studies were performed in cooperation with different organisations within the consortium, in various partnering countries, each operating within their regulatory and legal framework. Each of the participating countries had a different degree of prior experience, allowing for active knowledge transfer during multiple workshops evaluating commonalities and differences between the case studies and the evaluation approach. The strong international collaboration between the industry partners and other WP-leads resulted in improvements to the Well Screening Tool and a set of recommendations and learnings for re-using existing oil & gas wells for CO_2 storage from the end-user perspective.

4.2. Dealing with change

Throughout the duration of the project there have been frequent changes to the team, at Project Coordination (TNO) level and for the leadership of various WP's (e.g. WP-3, 4 & 7). This change of key members has not resulted in loss of knowledge nor delays in project delivery, for the following reasons:

- Well selected, not too big consortium with reliable, capable partners and nomination of skilled contact persons from all partners.
- Selection of relevant topics and clear objectives based on interests and dedication from all partners. The project was well-designed and well-managed from the beginning onwards.
- Good project plan with realistic timeline, balanced partner involvement and structured objectives that served the overall project goal.
- Regular and clear communication within the project on project management team and also on WP level (obligatory monthly meetings of PMT and WPs)
- Dedicated handover meetings to ensure a clear and smooth transition, often keeping previous team members involved on a need-to-know-bases.

In addition to above, the successful handover of the Project Coordinator role (3 times during the project) is also a result of:

- A living Project Management (PM) culture at TNO, with well-trained and experienced PM's tapping into an active educational framework. This enables that projects can be smoothly handed over from one TNO PM to the other.
- Remaining consistency in Project coordination style ensured no unnecessary changes to processes or way of working.

4.3. Gender equality

The REX-CO_2 project leadership and consortium organisations were committed to provide equal opportunities between men and women, though participation of females varying across organization was insurmountable. The leadership of the work packages was almost balanced at 45/55 between male and females, and just over one third of participants at project meetings, and workshops were female.

5. Spin-off & Outlook

5.1. Abandoned wells

The REX-CO_2 project targets exclusively wells that can potentially be re-used and therefore does not consider wells that are fully abandoned, while these can pose a significant risk to a CCS development by forming leakage pathways. Current standards and regulations (e.g. NOGEPA n.45, NORSOK D-010, ISO16530, Oil & Gas UK well integrity guidelines) do not consider CCS as part of the abandonment guidelines.

A MSc thesis study (Mozas, 2022) was initiated between TNO and the TU Delft to evaluate the conditions of abandoned wells utilizing the knowledge, network and Tool of the REX-CO_2 project. Javier established a framework for abandoned well evaluation, considering the main processes that contribute to leakage (e.g. chemical degradations of cement, mechanical integrity of well bore, abandonment conditions of a well prior to CCS), and quantifying these factors into a risk analysis. The framework is 2-fold; (1) a qualitative part based on the decision trees as developed for the REX-CO_2 screening Tool, and (2) a quantitative part based on probabilistic methods (Bayesian Belief Networks) for risk analysis, where both components function together as the full framework for leakage risk assessment.

The framework and evaluation method was tested and validated on several case studies. Screening of a wide range of abandoned wells showed that information on cement properties (e.g. elastic, shrinkage, thermal, additives) is often lacking in the abandonment reports. The developed evaluation framework has proven pragmatic and systematic, and showed that the current abandonment norms can be challenged.

The evaluation of abandoned wells raised significant interest among the E&P partners of REX-CO_2, as a (large) number of wells in their well stock portfolio has been abandoned and requires attention before FID can be taken on a CCS development.

5.2. Future of the Well Integrity Tool

In order to embed the Well Integrity Screening Tool fully into the E&P business as part of the CO_2 storage complex evaluation workflow, some limitations have to be overcome. The following modifications to the Tool were suggested by the industry partners of the REX-CO_2 project:

- Tailor the screening to a specific regulatory framework.
- Avoid the red-flags as currently shown by the traffic light system. It is recommended to consider a different metric to portrait the screening outcome, in order to not disqualify wells during the preliminary screening.
- Include the possibility to customise (e.g. subsea wells vs land wells, conversion of injector vs producer wells, minimum steel grade requirements).

The Tool, as currently developed, is seen by the E&P partners as a screening device able to communicate known risks and data/information gaps to upper management. It is a good workspace for the bundling of specific discipline work and a platform where expectations and design planning meet.

A logical direction for future Tool development would be to broaden the Tool by adding more technical features, more risk and design element analysis, customised to (at least) one environment, and to include the (qualitative) assessment of all reservoir penetrations as part of the storage complex.

Further development of the Tool would benefit from integration with the ongoing ACT3 CEMENTEGRITY project and to further mature the beta-version of the caprock cement integrity predictions and leak rates as currently implemented.

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