Deliverable 4.4

Injector well and injection facilities design: methodology, definition, and recommendations

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Disclaimer

Executive summary

This document serves as a high-level guide for the design process of a CO_2 injector well and its related facilities. In general terms, the knowledge from Oil & Gas industry is applicable to CO_2 injector well but taking in mind the most notable differences: the need to ensure an ideal pressure and temperature to inject the CO_2, the casing material to avoid corrosion, and the HSE processes to monitor the progress of the CO_2 plume.

The deliverable **"Injector well and injection facilities design: methodology, definition and recommendations"** facilitates the task 4.2.1 "Different well design alternatives electing a final design based on technical, economic and HSE criteria" and partially comprises the task 4.2.3 "Capture Transport, and storage facilities outline", including only the storage facilities section.

The task 4.2.1, focused on the pilot well, is planned in three main steps: **1) Proposal of different well alternatives, considering geological and hazards information, 2) Selection of final well design after technical and economical iterative assessments, and 3) Generation of technical and HSE plans of final well design (well construction, permits, operational, logistic and maintenance plans, HSE, emergency response, and well containment plans)**. Specifically, deliverable D4.4 sets the main workflows and recommendations to help each team to perform these tasks. The works performed following described methodology will contribute to the Pre-FEED study (Optimized pilot design feasible for a pilot project) that will be presented and put in common in the Milestone 18, in the month 54, (October 2025): "Presentation of a feasible optimized pilot design".

The task 4.2.3 consists of identifying capture technology applicable to selected CO_2 sources, transport opportunities considering the CO_2-stream quality and volume. The focus of the task are the injection facilities, mainly compressors, boosting pumps, heaters, etc.

Firstly, for being able to propose different well alternatives, considering geological and hazards and selecting the final well design, the main workflow proposed consists of what is outlined in the Well Construction workflow chapter. Secondly, we will outline a roadmap to develop the technical and HSE plans and remedial actions for a pilot well implementation. Finally, some recommendations and workflows regarding the definition of the injection facilities will be presented as per task 4.2.3.

Recommendations regarding capture and transport facilities (task 4.2.3) and regarding MMV (Measuring, Monitoring and Verification, task 4.2.2) are out of the scope of this report.

Contents

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1. Introduction

Wells are necessary to verify the existence of adequate storage formation and seal, to test it, and to inject CO_2 from the surface. Its design and execution must follow a methodology of technical risk management and operations that aim to ensure safe, efficient, and environmentally responsible well construction.

This document serves as a high-level guide for the design process of a CO_2 injector well and its related facilities. In general terms, the knowledge from the Oil & Gas industry is applicable to CO_2 injector well, but considering the most notable differences: the need to ensure an ideal pressure and temperature to inject the CO_2, the casing material to avoid corrosion, and the HSE processes to monitor the progress of the CO_2 plume.

Essential data that influences the technical work related to CO_2 injector well design would be provided by the output of the dynamic model. However, in its early stages, this information is still ongoing. Well design concept is needed to feed conceptual development design (task 4.1) and its preliminary economic evaluation (task 4.4). For this reason, this document will serve as a guideline in the pre-planning stage, when most of the technical data are not available but key parameters need to be identified and considered.

2. Well Construction workflow proposal

The Well Construction workflow must be applied as a baseline that establishes the sequence in which proposed activities will occur and their relationships under a project management approach, as described in the Figure 2.1.

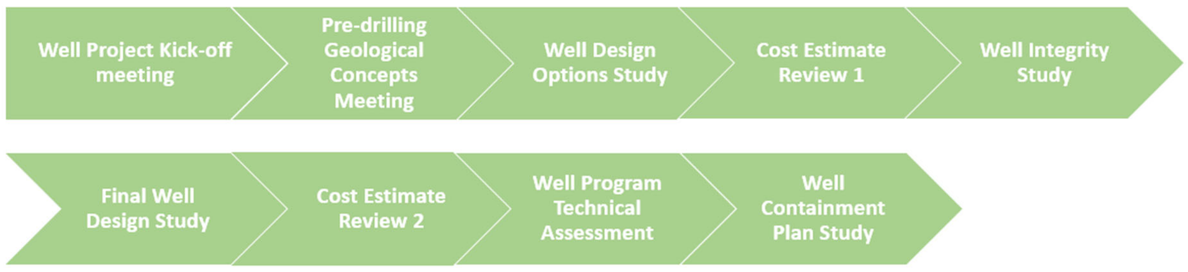

Figure 2.1: Well construction workflow proposal.

- **Well Project Kick-Off Meetings**: This activity works as a workshop event, with the participation of experts from WP2, WP3, WP4 and WP5. The objective is to provide technical, process, and project management information to define expectations, goals, limitations, and objectives.

- **Pre-drilling geological concepts meetings:** Formalise the delivery of the relevant information from WP2, WP3, and WP5 to WP4 to provide all the necessary information for the integral well planning. Present the information referred to well data, well objectives, available information, coordinates, geological and reservoir information. The first step (conceptual) is planned to occur from November to February 2024. Further steps need to incorporate significant outputs from static and dynamic modelling, proposed from July 2024 to April 2025.

  - Include, as one of the main inputs, the shallow hazards and other geohazards, and the geomechanically analysis results.
  - List data acquisition services required and the corresponding programmes: mudlogging, sampling, logging, coring, etc.
  - Provide offset wells information and analogue wells for drilling parameters review.
  - List potential drilling hazards.
  - Well test requirements.
  - Well monitoring requirements.
  - Expected life of the well.

- **Well Design options study:** The main objectives of the step are to provide the project team with feedback on design options and to define long-lead items requirements. Typical sources of relevant input include (UNE-EN ISO 16530-1:2017):
  - Offset wells, field operation history (downhole samples, formation pore pressures and strength, subsurface hazards).
  - Local studies of surface and subsurface conditions (seismic, reservoir model, seafloor, topography, subsidence).
  - Lessons learned with respect to well integrity from other wells or projects in similar conditions.
  - Anticipated life cycle changes or well operating limits.

  This task will be completed after dynamic simulation is ready (WP3, Task 3.2, July 2024), to provide output data for the specific well design alternatives. Expected delivery date is before December 2024. A workshop event should be scheduled to discuss all the proposed alternatives.

  - Decide options to optimise well design work:
    - Define well objectives, such as the subsurface target, well type, life expectancy, or injection capability with the anticipated effluent composition, and possible changes over the life cycle (UNE-EN ISO 16530-1:2017).
    - CO_2 delivery conditions (pressure, temperature, and composition).
    - CO_2 conditions at reservoir level.
    - Ranges of injection rates.
    - Wellbore diameter.
    - Vertical or deviated well.
    - Completion (standard or CO_2 resistant (chrome)).
  - Allows for the selection of the optimum well design from other relevant options later in the project.
  - Preliminary well completion options and monitoring plan.

- **Cost Estimate Review 1:** A review aimed to assess the cost estimate to assist the presentation for future approvals for funding once the Pilot Strategy Pre-Feed assessment is presented in April 2026. (Defined by task 4.4)

- **Well Integrity Study:** A Quality Assurance event performed to ensure well design and operational plans provide adequate well integrity for the life of the well. Ensure that well integrity elements are part of the Well Design Option. (UNE-EN ISO 16530-1:2017)

    - Identify the anticipated rock mechanical and subsurface hazards that can threaten well integrity over the anticipated life cycle of the well, e.g., faults, fractures, pore pressures, temperature, H_2S, CO_2, solids production, shallow gas, high pressure stringers, chalks, moving salts, permafrost, subsidence and earthquakes.
    - Provide any information pertaining to surface hazards and anticipated changes that can affect well integrity over the anticipated life cycle of the well, e.g., location, environment, urban planning, proximity to lakes, rivers, subsea, offshore, risk of ordnance, other operations or industrial activities, risk of subsidence, flooding, etc.
    - Identify the hazards associated with existing wellbores, abandoned wells, condition of the offset wells, related environmental issues, directional well path, etc.
    - Provide a combined hazard risk register from the identified and confirmed hazards for surface and subsurface conditions for the basis of design.

- **Final Well Design Study:** The aim is to review and agree on all elements of the Final Well Design (and operational plans) which may affect the achievement of project objectives. (Milestone 18, Month 54)
    - Reach agreement on well design and freeze the concept.
    - Review and agree on all elements of the Final Well Design that affect the well integrity.
    - Review and agree on all elements of the Final Well Design (and operational plans) which may affect the ability to reach project objectives.
    - Final well completion design and monitoring plan.

- **Cost Estimate Review 2:** Ensure that well time and cost estimates follow the standard cost accounts. (defined by task 4.4. after or in M54).

- **Well programme technical assessment:** This mechanism aims to support decision-makers by providing assurance that technical risks and their economic implications associated with investment proposals presented for approval have been identified, considered, and managed. This event takes place at the end of the well construction project's conceptualization phase and the cost estimate review. (Month 54 or later)
    - Review the well construction plan.
    - Review the HSE Permits Plan.
    - Review Emergency Response Overview.
    - Review logistics elements.

- **Well Containment Plan:** A Quality Assurance event performed to review the well containment response plan. It reviews the response organisation structure, equipment, and procedures and assesses the impact on well design (e.g., wellhead, relief well planning, etc., Month 58 – Pre-Feed Dossier)

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- Basis of Design
- Blowout Scenarios
- Emergency notifications
- Operational Procedures
- Capping Deployment Procedure
- Forms

3. Pre-drilling geological concepts - Key parameters required for well design.

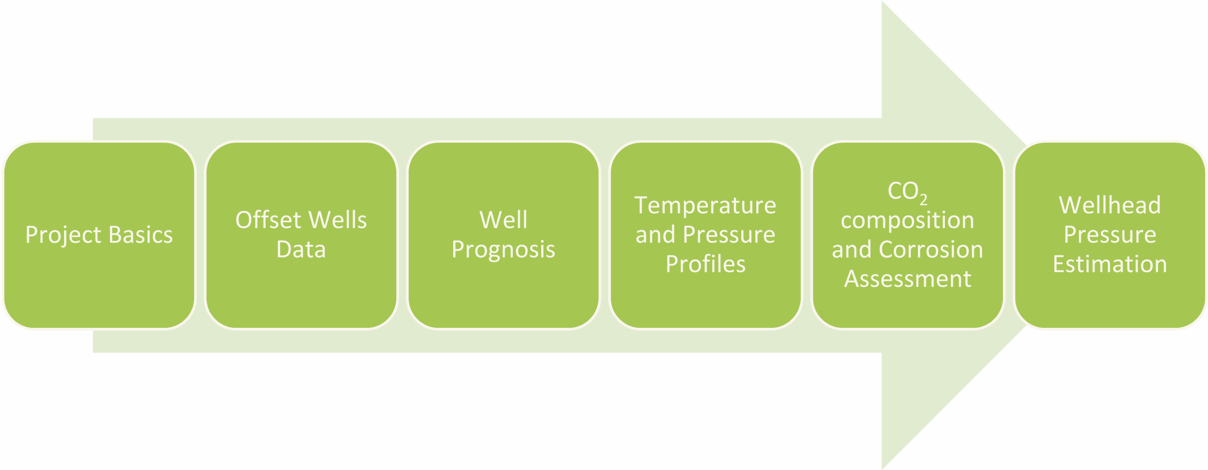

Figure 3.1: Workflow for Pre-drilling geological concepts and key parameters for well design

3.1 Project Basics

Regions must provide the extent of the storage formation, the outline of the different prospects or traps identified, an outline of the fetch/catchment areas outside the closures, and preferred areas of the well location options prior to dynamic modelling.

As a recommendation, to determine the preliminary coordinates of the well location, for those projects with conventional structural closures, it may be an option to select the location based on fill and spill analysis of the trap and migration pathways of the CO_2 plume towards the top of the reservoir grid.

It is of major importance to collect the data available from offset wells: those at a relatively close distance from the storage location, and also those wells that are far from the storage location but share similar play characteristics such as a similar depth of investigation, overburden, reservoir lithology, and depositional environment.

Finally, the analysis of the environmental protected areas nearby the storage are key to discard locations that might present HSE-related obstacles or restrictions for drilling activities.

3.2 Offset wells data

To facilitate the task of well design, a critical review of the analogue wells (previously drilled or legacy wells in the area of interest) is a key step. How those wells were designed, the number and diameter of the sections needed to reach the same target of CO_2 storage, and other relevant data will offer valuable information to the drilling engineer for the definition of the injector well.

The drilling hazards that those wells faced are also important since the same problems can occur in the injector wells, such as gas pockets that may be drilled at certain depths, faults or instabilities, and problems in the ground to locate the drilling rigs.

Any drilling event, such as tight spots where the drilling string got stuck, circulation losses when drilling through permeable or fractured formations in the overburden, or any fishing operation that the offset well had to complete.

Understanding the nature of any non-productive time that the offset wells encountered, such as waiting on weather (WOW in the drilling daily reports) or Blow Out Preventer (BOP) issues that are common and may suppose loss of time in the operations, and needs to be accounted for when estimating the amount of time needed to drill the injector. In the area of interest, there may well exist seasonal restrictions for operations that must be considered.

The drilling performance (ROP – Rate of Penetration) in every formation of the overburden and the reservoir will also help to estimate the possible duration of the injector wells.

Finally, the cost of the wells, if available, could be useful as an indicator to estimate the cost of the proposed well (considering time and market).

3.3 Well Prognosis

With the information collected in the previous steps, we should be ready to present an estimation of the well prognosis, including the formation of interest, reservoir, seal, overburden, basement, the depths of each formation, the coordinates of the well location with its reference system, etc.

From the WP2 output, a stratigraphic description of each unit is needed along with an estimation of the permeability, porosity, and pressure of every formation that the wells need to drill through. This document is to be produced by geosciences teams.

3.4 Temperature and Pressure Profiles

- Estimate the pressure profile of the prognosis well (s) based on offset well data, including leak off tests (LOT) of formation integrity tests (FIT), and pressure obtained from DST data.
- Calculate hydrostatic, pore, overburden and fracture pressure curves.
- Calculate the temperature profile (geothermal gradient) based on offset data, BHT (Bottom's Hole Temperature) and Horner plots.

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3.5 CO_2 Composition Assessment

Analyse CO_2 stream composition data for the selected source, possible H_2S presence in the formation, pressure and temperature of the reservoir, HO_2 (hydroperoxy radical) content (if any), impurities, expected flow rate, CO_2 flux pressure and temperature, injection cycles (potential steps, transient times) etc. (some data may come from WP3).

3.6 Well Head Pressure (WHP) Estimation

- 1D Model (i.e., Vertical Lift Performance vs. Inflow performance relationship model) for WHP estimation over time for the specific flow of captured CO_2. See reference: (Production Technology webpage, s.f.).
- Compression – Boosting options for CO_2 based on the WHP required to match the injectivity without compromising the fracture pressure.
- Determination of pressure losses in the pipeline from the compression point.
- Determination of the minimum power required by the compressor to produce the desired WHP considering the pressure losses assessment.
- Determination of tubing size to minimise the pressure required for injection.
- Run Sensitivity: tubing size, skin, permeability, etc. Reservoir and completion teams should clarify technical aspects like lower completion type: open hole, screens, cemented liner, slotted liner and others. A workshop between reservoir and completion teams is recommended.

4. Well Construction Guidelines

4.1 Class VI Wells (Class VI Wells used for Geologic Sequestration of Carbon Dioxide, s.f.)

For a Pilot Injection well construction, local regulations will apply. For well construction guidelines purposes, it's useful to take Cass VI as a guideline, but this normative does not have to be compulsory.

The Class VI well requirements are designed to protect public health and Underground Sources of Drinking Water (USDW) from the unique nature of CO_2 injection for Geological Sequestration, including the:

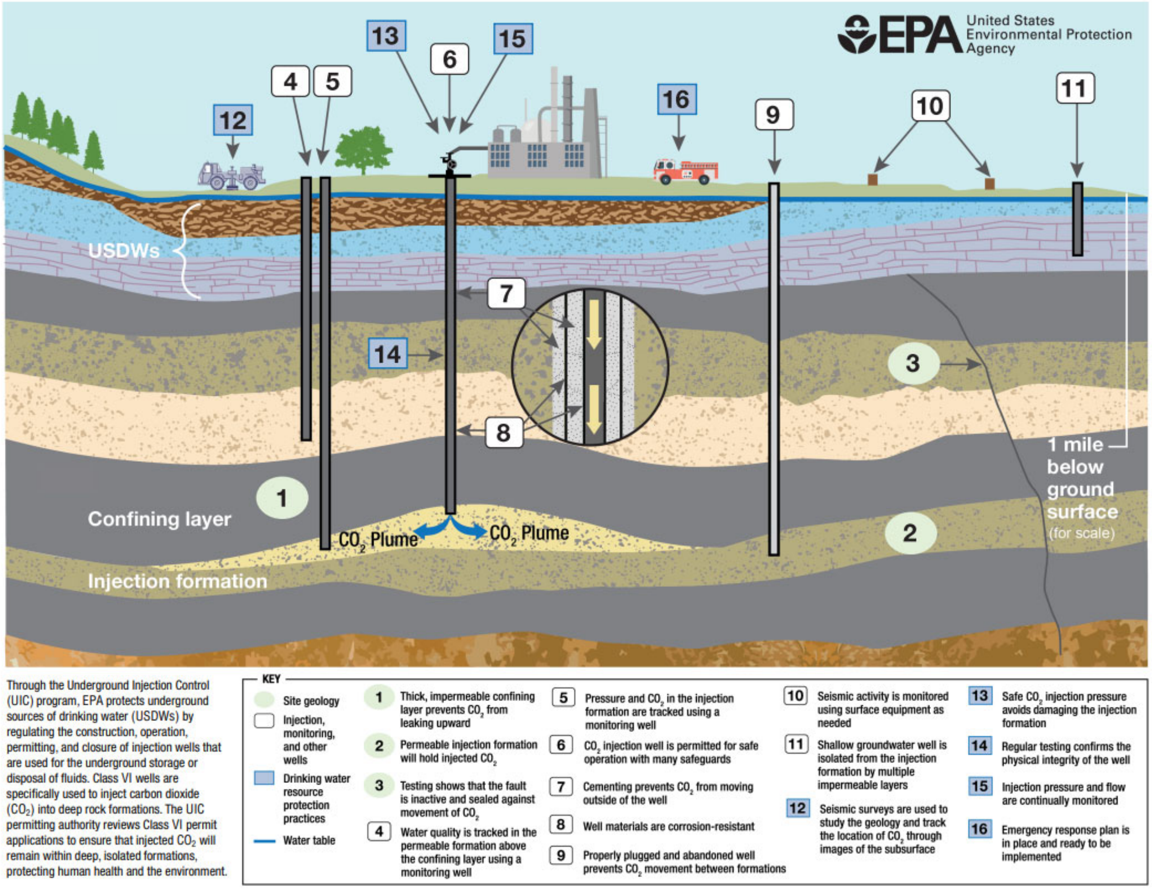
- Relative buoyancy of CO_2.
- Subsurface mobility.
- Corrosivity in the presence of water.
- Large injection volumes.

Requirements include:

- **Site characterization** requirements to ensure the geology in the project area can receive and contain the CO_2 within the zone where it will be injected, including that **induced seismicity is not a concern**.
- Requirements to predict the extent of the injected CO_2 plume and associated pressure front for the project using **computational modelling**, and to **identify and address any deficiencies**

of existing wells within the Area of Review (AOR) through corrective action. The Area of Review includes the area where the injected plume and its associated pressure front may impact pore fluids.

- **Well construction requirements** to ensure the Class VI injection well is constructed in a manner that will **prevent any CO_2 from leaking** outside of the injection zone.
- **Testing and monitoring** requirements to monitor the integrity of the injection well, groundwater quality, and the movement of the CO_2 plume and pressure front throughout the life of the project, including after CO_2 injection has ended, until the permitting authority determines no additional monitoring is needed to ensure that the project does not pose an endangerment to drinking water.
- **Operating requirements** to ensure the injection activity is appropriate to the well's construction and geologic characteristics so that it will not endanger drinking water resources or human health.



Through the Underground Injection Control (UIC) program, EPA protects underground sources of drinking water (USDWs) by regulating the construction, operation, permitting, and closure of injection wells that are used for the underground storage or disposal of fluids. Class VI wells are specifically used to inject carbon dioxide (CO_2) into deep rock formations. The UIC permitting authority reviews Class VI permit applications to ensure that injected CO_2 will remain within deep, isolated formations, protecting human health and the environment.

1 Thick, impermeable confining layer prevents CO_2 from leaking upward

2 Permeable injection formation will hold injected CO_2

3 Testing shows that the fault is inactive and sealed against movement of CO_2

4 Water quality is tracked in the permeable formation above the confining layer using a monitoring well

5 Pressure and CO_2 in the injection formation are tracked using a monitoring well

6 CO_2 injection well is permitted for safe operation with many safeguards

7 Cementing prevents CO_2 from moving outside of the well

8 Well materials are corrosion-resistant

9 Properly plugged and abandoned well prevents CO_2 movement between formations

10 Seismic activity is monitored using surface equipment as needed

11 Shallow groundwater well is isolated from the injection formation by multiple impermeable layers

12 Seismic surveys are used to study the geology and track the location of CO_2 through images of the subsurface

13 Safe CO_2 injection pressure avoids damaging the injection formation

14 Regular testing confirms the physical integrity of the well

15 Injection pressure and flow are continually monitored

16 Emergency response plan is in place and ready to be implemented

Figure 4.1- Class VI Risk Mitigation Graphic from www.epa.gov (Underground Injection Control (UIC) Program)

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- Requirements to **plug the injection well** in a manner that will not allow fluid movement that endangers drinking water resources.
- Requirements for the operator to establish and maintain **financial instruments sufficient to cover the cost of corrective action**, plugging the injection well, post-injection site care, and emergency and remedial response for the project (i.e., financial responsibility).
- Requirements to develop and maintain **a site-specific emergency and remedial response plan**.
- Requirements for the Class VI well owner or operator to **report all testing and monitoring results to the permitting authority** to ensure the project is operating in compliance with all permit and regulatory requirements.

4.2 Well Design

According to the ISO norm Procedures ISO 27914:2017, the wells designed for use in CO_2 storage projects can include injection wells to deliver CO_2 to the storage unit, monitoring wells to measure and record necessary information, and pressure relief (formation fluid extraction) wells for pressure management of the storage unit. In the context of the PilotSTRATEGY project, at least one injection well must be designed. For monitoring well, it is possible to use an already drilled legacy well to install a pressure gauge or any kind of sensor such as DAS technology (fibre optic deployment in the well with an interrogator installed to measure pressure, thermal effects, seismicity, etc.). The use of legacy wells for monitoring purposes requires a re-entry feasibility assessment.

It is not recommended to use legacy wells for any other use, such as injection or producer for pressure relief without an extended integrity assessment. These assessments are often very hard to perform due to the lack of data available for these wells, and moreover, the conditions of the wells could have been degraded after the last evaluation performed when the well was drilled. Expansively shales, ground movement, cement degradation, and casing corrosion could impact the integrity of the well, making it risky to re-use it for the mentioned purposes.

The use of deviated wells can improve the injectivity of the formation. The design, planning, and drilling of wells shall adhere to stated project objectives and minimise impact on any protected groundwater zones or other identified resources. These project objectives should be implemented when task WP 4.1 is completed with the selection of the final strategy.

Drilling plans should document the potential for fluid invasion and formation damage when drilling through the target storage unit(s).

The drilling and cementing plan should be based on standard engineering considerations like those used in oil and gas wells, and for CO_2 storage project-specific factors including:

a) Longevity of, and abandonment requirements for the well.
b) Intermediate and long-string casing requirements and the need for corrosion-resistant alloys.
c) Cement formulation and placement.
d) Location and orientation of potential migratory paths from the storage unit to nearby geological formations.

The design of all wells shall evaluate location, storage complex characteristics, and material requirements specific to their function at the storage site, as per the following:

a) The design of injection wells to deliver CO_2 to the storage unit shall evaluate injectivity, permeability, and porosity of the storage unit to avoid excessive subsurface pressure interference and to ensure acceptance of the anticipated volume of CO_2.

b) The design of monitoring wells shall support the specified monitoring purpose and measurement objectives, including longevity and access for remediation or modification.

4.3 Estimation of logging, coring, and testing

For each region, an assessment of the amount of information that is missing for the correct geological and technical characterization must be done to propose a coring, logging, and testing programme in the proposed well. This analysis must be done, including the cost and the rig time necessary to perform the activities, based on the next considerations.

- Logging Programme
    - Number of runs and selection of tools (standard Suite, magnetic resonance, image logs).
    - Is it necessary to acquire checkouts or VSP?
    - Is it viable to acquire sidewall cores?
    - Study the alternatives of acquiring “logging while drilling” data (LWD) to replace wireline operations with the associated cost savings.
- Injection Test units
    - Define number of the units to test prior to FID (Final Investment Decision).
    - Formation test design to define test duration, maximum depth of test investigation, and all other relevant variables.
- Coring Programme
    - Decide the number of cores in the overburden, seal, and reservoir sections.
    - Continuous core or selected zones.
    - Proposal of lab analysis for core data.

4.4 Tubulars

The norm (ISO), I. S. (2017) *ISO 27914* states that tubulars such as **well casing, production tubing, and liners** are components of wells that are essential for long-term well integrity and for the injection and production of fluids. They provide barriers that ensure the protection of groundwater resources and the safe operation of CO_2 injection or fluid production at the geologic pressures and temperatures encountered within storage complexes.

The conductor pipe or casing prevents caving and washout (loss of material from the borehole wall) at the rig base and encases the cement for the surface casing at ground level. Once in place, the conductor casing should be secured and may be cemented to maintain integrity around the casing and to prevent washouts. The well shall be drilled out through the conductor casing to below protected groundwater, and the surface casing(s) shall be run and cemented back to the surface using single or multiple strings of casing and cement if it is necessary to protect any groundwater encountered.

Well surface casing shall be set and cemented at sufficient depths to ensure a) isolation of protected groundwater sources, and b) control of the well under maximum formation pressures and operating pressures prior to the next casing interval.

The design of the tubing string shall apply the same material and environmental requirements as applied to casing design, including whether corrosion-resistant alloy is required and in what location(s) of the tubing string. Depending on the well design (which in turn depends on the required flow rate to be injected and the project time), only the production casing that will be in contact with the CO_2 needs to be of a specific material, the other casing strings do not need to be specifically designed for CO_2. The expected maximum injection rate of the CO_2 stream required by the well to meet project objectives should be used to determine the minimum diameter of tubing required. The maximum injection pressure should be used to determine the weight and grade of tubulars for the well. Packers of adequate internal diameter should be used where subsequent wireline work might be desired during the life of the injection well.

One important thing to consider in the CO_2 pilot well projects is the behaviour of CO_2 in the transition from dense to gas phase; the rapid cooling associated with the decompression of dense phase of CO_2 may result in very low temperatures that could exceed the design limit of the well construction components and the hydrate formation under the appropriate conditions. It is mandatory **to include diagrams with the operation limits of the material based on the rating of the components.**

4.5 Well Completion

The wells must be completed in a manner that meets the project goals (as determined by the strategy selected in the WP4) while maintaining wellbore integrity. A detailed completion plan shall be developed and reviewed by the legislator to address the project goals.

The wells must be designed to place a well-bonded cement sheath between the casing and the formation, from the casing shoe to the top of cement, as required. The cement should: a) structurally support the casing; b) resist all expected well and formation loads; c) seal the annulus to isolate pore pressures in covered zones or to isolate different reservoir intervals; and d) protect the casing from corrosive fluids in relevant zones (ISO, I. S. (2017) *ISO 27914).*

The cement and casings must maintain hydraulic isolation across all strata above the storage unit and across all protected groundwater source zones above the storage unit.

The cement must be evaluated to ensure that no leaks are detectable. Pressure testing of the casing should only be performed after significant cement slurry gel strength has developed. Defective cement sheaths may be repaired using remedial methods and materials that meet the structural support and sealing requirements of the primary cementing design.

4.5.1 Well Design. Drilling & Completion (D&C) recommendation

- Estimate the number of sections to reach the depth of investigation.
- Define the hole section, casing type and diameter & tubing size.
- Analyse benefits of horizontal vs vertical drilling to reach the target depending on the reservoir heterogeneity, beds dipping, surface above-ground restrictions to drilling, etc.
- Decide on the number of injection wells and drilling strategy to reach the Storage objectives.
- Decide the completion options for injection: Multi-zone reservoir? single storage tank?, material? etc.

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4.6 Corrosion Control

The CO_2 stream may have corrosive constituents in addition to CO_2, such as NOx, SOx, H_2S, H_2O, and O_2 that can damage the steel components.

So, the CO_2 stream shall be monitored to determine the presence of these constituents. Maintenance should include external coatings. A monitoring programme should determine the effectiveness of the corrosion mitigation efforts, including chemical analysis of the injected fluids for indications of trace metals, corrosion coupons placed in the injection stream, and ultrasonic or other non-destructive testing of pipes for wall thickness loss.

4.7 Well abandonment

For the PilotSTRATEGY well design objectives, it is also necessary to consider the actions taken for abandonment of wells once the injection stage is completed.

During plugging, care must be taken to always maintain well control so that no injected fluids are released into the wellbore or the atmosphere. The CO_2 must be flushed into the reservoir, and the wellbore must be filled with a fluid to maintain the well control. Casing and cement integrity logs should be re-run and compared to the original baseline logs to confirm cement and well bore integrity. All open perforations must be sealed and plugged according to local regulations or international standards if the former are not available.

4.8 Well Time and Cost Estimations

To quantify the well time and cost, the next consideration may be clear:

- Consider well engineering costs (design, planning and operations)
- Investigate the performance of the analogue wells in the area
- Estimate the non-productive time based on the analogue wells
- Estimate logging, coring and testing time and cost.
- Estimate mob/demob time and cost (international and infield)
- Obtain drilling rig daily rate
- Search for drilling services daily rate
- Investigate material costs (drilling tubulars, completion material, logging, etc) and delivery times.

5. Well permitting roadmap and remedial actions

Recommendations regarding the generation of technical and HSE plans for final well design and **HSE emergency response** are the objective of this chapter.

Each country has its own regulations. In the Lopin (Spain) case:

- Request for investigation permit: Law 40/2010 (29th December, CO_2 Geological Storage).
- Communication of the initiation of research and investigation, and appointment of a facultative director, and submission of work plans: Law 22/1973 (21st July).

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- Environmental impact assessment (ordinary procedure): Law 21/2013 (9th December).
- Authorization for the execution of research wells: Law 22/1973 (21st July, Mining Law)
- Administrative authorization for gas transportation: RD 1434/2002 (27th December)

In France (Bouet et al, 2022), the regulation requires an exploration permit (‘Permis Exclusif de Recherche’) under the Environment Code (Env. Code art. L. 229-30) while the Mining Code details the permit procedure (Min. Code Art. R. 229-58) which include several supporting documents:

- Consent of the holder of the mining license or underground storage license if necessary;
- Technical report (including geology, as per art. 17 of Decree 2006-648);
- Location documents (maps, as per art. 17 of Decree 2006-648);
- The program of the planned exploration activities and financial commitment (art. 17 of Decree 2006-648);
- Environmental impact assessment (‘notice d'impact’, as per art. 17 of Decree 2006-648 which will change in 2024);
- Technical and financial capacities (Min. Code art. L. 114-3-1 and art. 4 and 5 of Decree 2006-648);
- Analysis of the environmental, economical and social effects of the project (Min. Code art. L 114-1 and L 114-2);
- Report of the environmental analysis (Min. Code art. L.114-2 and L. 121-6).

The different opinions from the administration are collected during the instruction and made available to the public on the website of the Prefecture of the departement before the start of the public participation process (preliminary consultation or public enquiry, as per Min. Code art. L. 114-2 -IV).

The turnover time for the administrative investigation of the permit application is typically about 2 years. The permit duration is up to 15 years (Min. Code art. L. 122-2). Important recent aspects of the attribution procedure are:

- A site follow-up committee (called ‘commission de suivi de site’) may be requested by the competent authority once a exploration permit application was submitted (Min. Code art. L. 114-4-1).
- An application for a new permit will be subject to a competitive tendering process (Min. Code art. L. 122-2) i.e. competing applications are allowed for 30 days after publication of the notice in the Official Journal of the French Republic.

Once the exploration permit is granted, each field activities aiming at characterizing the storage site will be subject to declaration or authorization of opening of mining works, as per in Mining Code. The content of the application depends on the type of works planned by the permit operator:

- Subject to declaration: non-intrusive exploration (e.g. seismic acquisition) activities described in the Decree n°2006-649.
- Subject to authorization: drilling and injection tests which according to Article 2 of the Ordinance 2022-534 follows the procedure for environmental authorization. The

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environmental authorization will be delivered according to the conditions of the Env. Code (Env. Code art. L. 181-1 to L. 181-23). The application for environmental authorization must include a minima the elements listed in article R. 181-13 of the Env. Code but needs to be tailored to the specificities of the project for which an authorization is required (Env. Code art. R. 181-5).

For injection tests performed as part of CO2 storage characterization additional requirements are set in the article R. 229-60 (Env. Code) and are as follows:

- Impact assessment as per Chap II, Title II of Book I of the Env. Code.
- Hazard study (Env. Code art. R. 181-5).
- The characteristics of injection, safety and control equipment.
- The justification for the quantity of carbon dioxide that it is planned to inject, the origin and the transport methods foreseen towards the injection well, the criteria which apply to the composition of the gas injected.
- The planned monitoring methods, in particular the measures taken to detect possible effects on the surrounding environment.
- The delimitation of the volume of the geological formation retained for the injection tests and, when this formation includes underground water tables, the justification by the applicant that nature has rendered it permanently unsuitable for other uses.
- The internal operation plan in the event of a disaster (organisational measures, intervention methods and necessary means which the operator acquires and implements to protect personnel, populations and the environment). Document to be drawn up by the operator.

Furthermore, mining works opening is subject to the constitution of financial guarantees (Min. Code art. L. 162-2) to cover the measures for stopping the work, for the surveillance of the site and ensuring the safety of the installations, for possible interventions in the event of an accident before or after the site is closed.

In Portugal, the regulation that establishes the legal framework for CCS is the Decree-Law 60/2012 (14th March, 2012), which was transposed from the 2009/31/EC - Geological Storage of Carbon Dioxide European directive. This regulation is only applicable to commercial CCS projects, and does apply to CO_2 storage below 100 k tonnes (pilot investigations or tests).

5.1 Environmental, Social, and Health Impact Assessment

The ESHIA is a tool used in the systematic evaluation of environmental, social, and health related impacts and must be included in the pre-feed final assessment of each injection site. It identifies and assesses potential environmental, social, and health impacts and ensures that appropriate mitigation and monitoring measures are designed and in place.

An ESHIA must be developed to meet the following objectives:

- Comply with legal requirements in the country of operation.

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- Comply with the operator company policies, standards, and public positions,
- Define the location's baseline conditions before the activity.
- Evaluate the potential impact of the activity and establish a mitigation plan.
- Enhance the positive impact of the activity.
- Prevent future liabilities resulting from the activity after decommissioning.
- Avoid claims from stakeholders.
- Facilitate internal decision-making regarding environmental, social, and health issues.

For the analysis of the PilotSTRATEGY Project the typical contents of the ESHIA should be:

5.1.1 For offshore Portugal Project:

- Impact on sea water quality.
- Modelling of potential accidental CO_2 spills.
- Characterization of wastewater effluents.
- Impact on marine fauna and flora and seabed.
- Characterization of cuttings discharge (in case of discharge to sea).
- Impact on water quality (in case of well testing operations).
- Interaction with other sea users (stakeholders).
- Visual impact and interaction with coastal activities.
- Impacts on local economies, public health and livelihoods.
- Indirect social impacts.
- Impacts on the health of nearby communities from project emissions and releases during exploration in shallow waters.
- Waste generation and a Waste Management Plan based on the principles of reduction, re-use and recycling.
- Mitigation and monitoring measures.

5.1.2 For Onshore projects (Paris Basin and Lopin)

- Impact on water quality.
- Characterization of wastewater effluents.
- Modelling of potential accidental CO_2 spills to surface waters or atmosphere.
- Impact on biodiversity (local fauna and flora).
- Waste generation and a Waste Management Plan based on the principles of reduction, re-use and recycling.
- Impact on air quality (in case of well testing operations).
- Impact on the local economy, livelihoods, services and infrastructure.
- Impacts on cultural property and customs.
- Impacts on the health of nearby communities from project emissions and movement of materials through the community.
- Diseases affecting community health.
- Project-related changes to land use, water use, air quality and energy supplies that could directly or indirectly affect community health.
- Impacts on land use, soil contamination and water and groundwater resources contamination due to the construction of new roads and/or deforestation.
- Mitigation and monitoring measurements.

5.2 Emergency Response Plan

Typical examples of scenarios to be considered in the required Emergency Response Plans (and which could require a specific emergency response plan) are:

- Fire and explosion.
- Evacuation.
- Well containment and blowout contingency plan.
- H_2S emergency response plans.
- CO_2 spill contingency plan.
- Medevac.
- Pandemia.
- Search & Rescue, including Man Overboard for the offshore case.
- Extreme weather conditions.

Proper communication with local authorities shall be established according to local regulations (Police, Military, Health Service, Coast Guard, etc.)

6. Facilities Design

A reference protocol is available for engineering considerations of surface facilities for a CCS project (Satoshi Motohashi et al, 2011). Its author set four technical issues for the surface facilities, CO_2 transportation, removal of impurities in the CO_2 gas, the liquefied CO_2 heater models, and the shaft seal system for CO_2 pumps.

The steps recommended to perform a draft design of the storage facilities for the injection of CO_2 are summarised in the next chart:

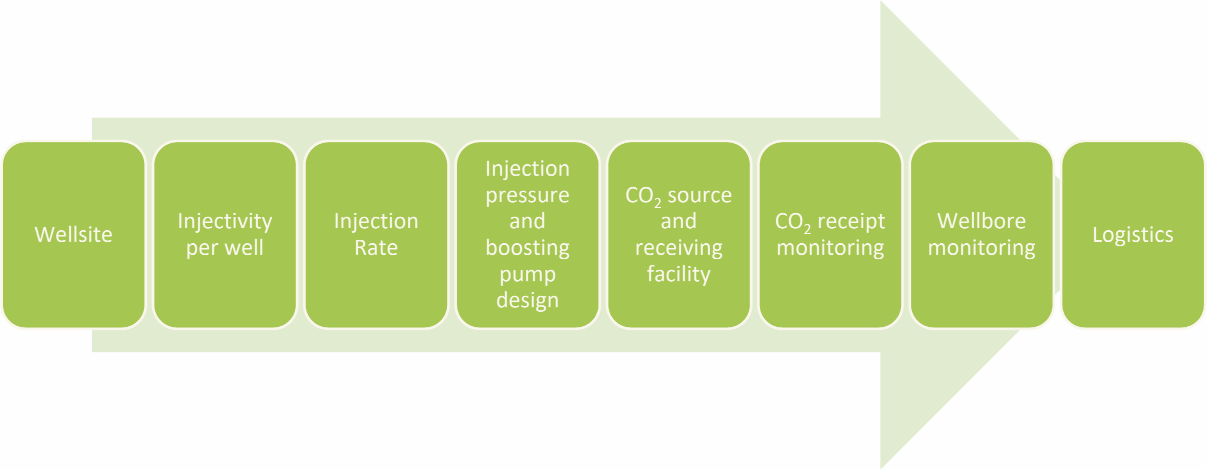

Figure 6.1: Workflow for facilities design

6.1 Wellsite

The selection of the wellsite will be based on the output of the dynamic model and the maximisation of the storage capacity according to Task 3.2 of WP3 (Simulation) , considering the limitations in pressure and other risks provided by Work Package 5 (Safety and Performance).

The ISO Norm 27914 states that the selection of the wellsite should consider adequate access to the wellhead by rigs and service vehicles for drilling, inspection, maintenance, etc. It is also important to avoid topographically low areas where the density difference between CO_2 and air might cause CO_2 accumulation in the case of a spill. Finally, areas in which interference with existing and future economic activities such as mining, agriculture, fishing, etc. should be avoided when possible.

Additionally, an evaluation of the surface and subsurface activities beyond the CCS operations should be performed to evaluate any potential impact on the integrity of the storage complex.

6.2 Injectivity per well

The amount of CO_2 that each well can inject must be an output of the dynamic model resulting from the WP3. The limits for the injection are the fracture pressure of the seal and the reservoir, since induced fractures should be avoided in a CCS project. A minimum threshold limit of 90% of the fracture gradient must be applied to guarantee a correct injection without producing hydraulic fractures in the formation of flow or in the sealing unit (Naser et al., 2010).

It is a possibility that some preliminary results of injectivity need to be delivered before the final results of the dynamic model become available. In that case, it is recommended to run a 1D model of injectivity performance using Prosper® or another similar numerical solver.

The main parameters that this kind of solvers require are thickness, porosity, permeability of the formation, the estimated skin of the well, the injection tubing diameter, the pore pressure and fracture pressure of the formation at the well location, among others.

To estimate the pressure at a particular location where no well data is available, a 3D geomechanical model would be optimal. In the absence of such models, offset wells are to be used for determining the worst, mean, and best-case scenarios for the pressure window for CO_2 injection.

6.3 Injection rate

The maximum injection rate per well will set the project's injectivity/well threshold; however, injection rate will also be determined by above-ground variables and by the project strategy defined in Task 4.1.

In the case of a pilot project strategy, some countries establish a maximum amount of CO_2 to be injected through the project's lifetime of 100.000 t; in such a case, the injection strategy and all associated well-design variables should be accommodated to such limitations.

In the case where the strategy is to develop a project to upscale it into a commercial development, well and engineering design should consider the transition from the pilot to the commercial phase to optimise the design in advance.

However, if the strategy of “minimum cost” or “secure plume monitoring” is preferred, then the project may be successful by injecting around 30 kt.

6.4 Injection pressure and boosting pump design.

The CO_2 must be compressed before entering the formation to a limit where it is able to overcome the reservoir pore pressure.

The optimum injection pressure to guarantee the volumes of CO_2 committed in our decided strategy will also be an output of the dynamic modelling.

As stated in the injectivity chapter, there will be a limit to the pressure that we can transmit into the reservoir, which will depend very much on the well design and the reservoir permeability.

The injection pressure will determine the characteristics of the compressor or boosting pump required to inject the CO_2 into the formation.

The booster pump and the injection pump pressurise liquid CO_2 from the inlet pressure to the required injection pressure. The lubrication method (liquid-lubrication or dry-gas seal) needs to be selected as well.

6.5 CO_2 source and receiving facilities

The characteristics of the CO_2 stream and the impurities will be determined by the capture process and the source industry. Some specifications may be requested to the emitter, but there are also technical and economic limitations to the degree of purity that the CO_2 may reach at the injection inlet.

Several studies estimate the concentration and type of impurities in CO_2 streams from different carbon capture processes (Porter et al., 2015); when possible, the CO_2 source must be considered as early as possible in the design phase of the project given its potential impact on facilities and project design. Quantity and nature of impurities impact the choice of facilities’ metallurgy and might impact injectivity if CO_2 – reservoir interactions occur.

It is necessary to study the alternatives for the removal of impurities, such as the absorption method, the cryogenic separation method, or catalytic combustion. The adsorption method is more effective than other methods (Satoshi Motohashi et al, 2011).

The design of the transport facility for an injection project should comprise a study of 1) the construction period; 2) the local citizen’s consent (interaction with the WP6 : Societal Engagement); 3) the construction cost (output for task 4.4.); 4) the running cost (idem); and 5) the energy consumption. (Satoshi Motohashi et al, 2011).

To guarantee the supercritical state of the CO_2, it is necessary to employ heaters. Several methods are available on the market and it is necessary to compare them, such as hot water boilers or heat pumps. It is important to compare the methods in terms of energy consumption and CO_2 emissions.

6.6 CO_2 Receipt monitoring

The CO_2 stream received at the site must be continuously metered and periodically sampled at the custody transfer point to the storage facility for safety, regulatory, and accounting purposes.

The metering facility should include: ((ISO), 2017)

1. Calibration of meters at regularly scheduled intervals following manufacturers and industry recommended practices.
2. Recording of calibration measurements for accounting audit purposes.
3. Determination of the composition of the CO_2 stream at regularly scheduled intervals.
4. Measurement of pressure and temperature of the CO_2 to assure density.

6.7 MMV (Measuring, Monitoring and Verification).

These are the key areas to consider: atmosphere, biosphere, hydrosphere, wells, and geosphere.

The annulus between the CO_2 injection tubing and the casing must be monitored at the wellhead for pressure and temperature to provide data to support the assessment of casing, injection tubing, and packer integrity.

The wellhead annulus pressure shall not exceed the wellbore design pressure rating or regulated maximum pressure. The wellhead annulus pressure shall not exceed the wellbore design temperature rating or regulated maximum or minimum temperatures.

The wellbore should be examined periodically to ensure the injection fluid is not entering the annulus and annulus fluid is not entering the tubing or geologic formations penetrated by the well.

For monitoring purposes, it would be useful to evaluate the possible equipment deployed in the well, like pressure gauges, optic fibre, or samplers.

Example for MMV (Measuring, Monitoring, and Verification) plans for onshore projects (France, Spain). (*Recommended practices for measurement, monitoring, and verification plans associated with geologic storage of carbon dioxide, IOGP 2022*)

- Atmosphere. detecting but also quantifying any emissions to the atmosphere. Acquire baseline surveys. Appy Light Source – Eddy Covariance Technologies.
- Biosphere. The biosphere will be monitored for tracers as a contingency, and soil and flux measurements will be done at regular intervals. InSAR data is recommended.
- Hydrosphere. Periodically monitor groundwater geochemistry (groundwater wells)
- Geosphere.
    - 4D surface seismic
    - 4D DAS - VSP.
- Monitoring wells.
    - Downhole Pressure – Temperature
    - Downhole microseismometer (geophone – DAS)
- Injection wells.
    - Injection rate metering
    - Cement bond / casing integrity

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  - Tubing integrity
  - Annular pressure
  - Downhole sampling / Pressure – Temperature gauges.
  - DAS – DTS.

6.8 Logistics

The transport of CO_2 is also key to designing the facilities. Define the type of power supply for the compressor (renewable? Geothermal Energy? Electrical substation?)

- Review the means of transportation to the well site for both personnel and equipment.
- Identify the logistics contracts required for the injection project at each site.
- Estimate an initial logistics budget.

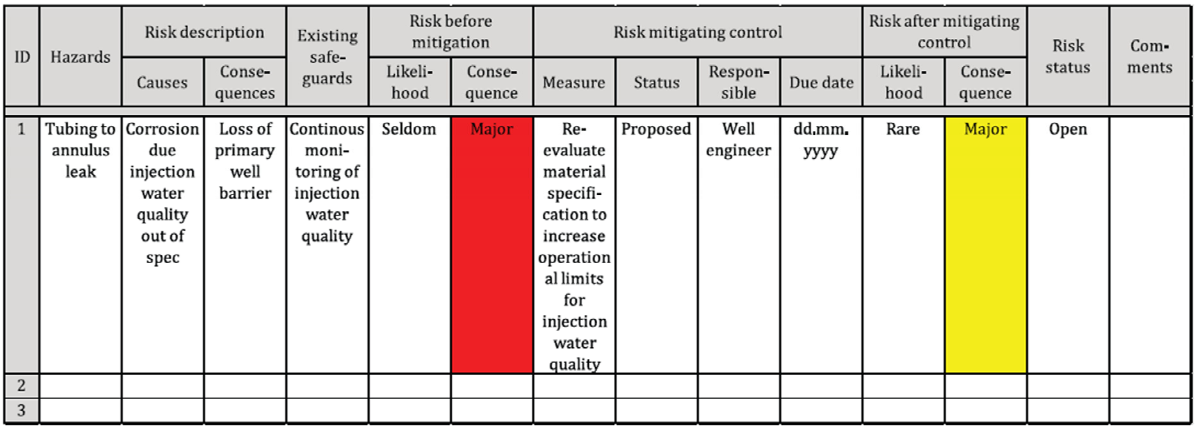
7. Output for WP5 (Safety and Performance): Injection Well and Facilities Risk Register

It is mandatory to perform a risk register to evaluate the main risks during the entire life of the injection pilot project concerning drilling and operating a pilot well, including project risk and management of major accident hazards. The risk analysis per item should include an estimation of the likelihood of occurrence and the impact on the project if the risk finally happens.

Some considerations for performing the risk register, among others, are:

- Are there environmental limitations? Bird-migration pathways, biodiversity protected land, etc.
- Is the risk of legacy well leaking correctly evaluated?
- Are the authorities engaged in the drilling of a CO2 pilot injection well?
- Analyse the uncertainties of the project.
- Are there drilling companies and logistic bases nearby?
- Will the CO_2 be available in the estimated quantities for injection test?
- Cost of logging tools, testing and coring – we suggest meeting service companies to correctly estimate the cost.
- Is the inflation estimated in the expected cost?
- Which are the opportunities that the drilling of a CO2 pilot well can bring?
- Are there service companies based in the area?
- Are there universities and academia close by willing to cooperate?

Once the risks are evaluated and corrected, select the risks that are of higher impact and likelihood to perform a Bow Tie assessment to provide information on how to prevent the hazard, or mitigate it in the event that it is not preventable, and evaluate the consequences of the hazard. It will be a key input info for the WP5 to run their risk models. **UNE-EN ISO 16530-1:2017.** This regulation serves as a reference of what a risk register should be.



ID	Hazards	Risk description		Existing safeguards	Risk before mitigation		Risk mitigating control				Risk after mitigating control		Risk status	Comments
		Causes	Consequences		Likelihood	Consequence	Measure	Status	Responsible	Due date	Likelihood	Consequence		
1	Tubing to annulus leak	Corrosion due injection water quality out of spec	Loss of primary well barrier	Continous monitoring of injection water quality	Seldom	Major	Re-evaluate material specification to increase operational limits for injection water quality	Proposed	Well engineer	dd.mm.yyyy	Rare	Major	Open	
2														
3														

Figure 7.1: Example of Risk Register (UNE-EN ISO 16530-1:20179).

Explanation of each item in Figure 7.1:

- **ID.** Each risk element should have a unique identification number for use as reference.
- **Hazard.** An event, condition or state involving increased risk of negative impact(s).The description should be short and to the point. Examples of hazards: casing leak, erosion, etc.
- **Risk description. Cause**. A description of the cause(s)/trigger(s) that can lead to the occurrence of the hazard.
- **Risk description. Consequence.** A description of the consequence(s) if the hazard occurs. The consequence refers to the possible effects of the hazard if it occurs.
- **Existing safeguards.** Existing safeguards relate to measures or barriers (technical or organizational) that are already planned or in place to prevent the hazard from occurring.
- **Risk before mitigation. Likelihood.** The likelihood of the consequence occurring, considering the existing safeguards. The probability is selected from predefined categories in the risk assessment matrix.
- **Risk before mitigation. Consequences.** An expression for the consequence of the hazard considering the existing safeguards. The impact is selected from predefined categories in a risk assessment matrix.
- **Risk mitigating control. Measures.** Probability- or consequence-reducing measures to mitigate the risk. For each risk, consider any risk-reducing controls that have the potential to reduce risk to within the effect of the existing safeguards. Each measure should be evaluated in accordance with the ALARP principle.
- **Risk mitigating control. Status.** The status of the control measure. The status of implementation of a control measure should be described
- **Risk mitigating control. Responsible.** Assign each control measure to a responsible person.
- **Risk mitigating control. Due Date.** Assign a due date for each control measure. This date is the deadline for implementing the measure.
- **Risk after mitigating control. Likelihood.** The Likelihood of the consequence occurring, considering the existing safeguards and the effects of planned control measures. The probability is selected from the predefined categories in the risk assessment matrix.
- **Risk after mitigating control. Consequence.** The Likelihood of the consequence occurring, taking into account the existing safeguards and the effects of planned control measures. The probability is selected from the predefined categories in the risk assessment matrix.

- **Risk Status.** The status of managing the risk should be described. Whenever a risk is closed or otherwise no longer relevant, it is recommended to change its status to closed. This will help in managing the risks.
- **Comments.** Any information that can be relevant to document or communicate may be added in the comments text field.

8. Work performed until the delivery of this document.

At the time of the production of this document (March 2024, Month 35), the project members do not yet have the necessary data to be more precise in the proposed designs. As a first step, the static model (DL 3.1 - 3.2, Month 33) will serve as input data for the elaboration of the dynamic model (DL 3.3, Month 39). The dynamic model provides important information from which the optimal location of the injector well can be determined (or different options), and the injection flow rate range and its associated pressure and temperature can be more accurately estimated.

These outputs are critical for the following steps. Drilling experts would propose several well design alternatives and associated facilities with greater accuracy, and the associated costs could be bounded within a narrower range of uncertainty. Accuracy will increase as the project and knowledge progress.

At the time of submission of this document, the following activities had taken place:

- **June 16th, 2023**. An online meeting was performed in which all regions presented the first approach to the injection area and well alternatives considering the preliminary data from the geological conceptual model. All regions showed a very preliminary analysis of probable well locations and the uncertainties they had been considering.

- **September 26th, 2023**. A project meeting focused on:
    - Reference Offset/Analogues wells information (typical well design of offset wells in the area, with their main targets, drilling hazards that those wells faced, drilling events such as losses or fishing operations, understanding the non-productive time, drilling muds they used, and any other issues).
    - Some regions also presented an estimation of the well prognosis for the future injection well in the PilotSTRATEGY proposal, including the total depth, the reservoir target(s), and the most likely location that is possible prior to modelling.

- **November 30th, 2023**. A follow-up meeting addressed the following topics, although most of the issues were kept open until other project data were available (scenarios, dynamic modelling, geological constraints, etc.):
    - The input data for pressure and temperature profiles in the wells of interest.
        - Estimate the pore pressure fractured gradient profile of the prognosis well based on offset data.
        - Leak off Tests availability.
        - Pore pressure obtained from offset well test data.
        - Temperature profile (geothermal gradient) based on offset well BHT (Bottom's Hole Temperatures) and Horner plots, if available.
    - Estimation of logging, coring, and testing needs.

- Logging Programme: Number of runs and selection of tools, checkshots or VSP, sidewall cores, acquiring LWD data instead of wireline logging.
- Injection test: Decide the number of units to test, the duration of the test, the maximum depth of investigation (proximity of faults or boundaries).
- Coring programme: determine the number of cores in the overburden, seal and reservoir sections; continuous core vs. selected zones coring; lab analysis estimation for core data.

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UNE-EN ISO 16530-1:2017 75.180.10 - Exploratory, drilling and extraction equipment. Including offshore structures

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