PilotSTRATEGY

Deliverable 5.3

Recommendations for safety and performance analyses of storage pilot in the Ebro Basin

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Non-technical summary

1. Project Overview and Objectives

This report summarizes a detailed study on the safety of permanently storing carbon dioxide (CO_2) deep underground in the Lopín site, near the town of Quinto, in the Ebro Basin. CO_2 is a major gas contributing to climate change. The technology being investigated, called Carbon Capture and Storage (CCS), involves capturing CO_2 emissions from industry and injecting them into suitable deep rock formations, where they can be safely trapped for thousands of years.

This study is part of the European PilotSTRATEGY project, which is exploring the potential for this technology in several regions, including the Lopín site in Spain.

2. The Geological Principles of Storage at Lopín

The safety of the Lopín site relies on geological principles that have been proven effective worldwide over millions of years. The site contains a multi-layered system where different rock types each play a crucial role:

i. An extensive, deeply isolated storage reservoir: A sandstone formation situated over 1,700 metres deep—far below the deepest freshwater aquifers used for human supply, creating a vast buffer zone that ensures complete isolation from surface ecosystems.
ii. An exceptionally robust, multi-barrier sealing system: The reservoir is capped by impermeable layers, primarily the Keuper Formation. This 400-metre-thick sequence of clays and evaporites represents a rock type known globally for its exceptional sealing capacity, as demonstrated by its natural ability to trap buoyant fluids like oil and gas over geological timescales.

3. Safety Assessment and Key Findings

A detailed risk analysis by experts has concluded that the pilot phase presents a very low-risk profile. This phase is designed to inject a limited volume of 100,000 tonnes of CO_2—a modest amount compared to the scale of natural geological formations, and a conservative threshold established by regulation specifically for research and demonstration purposes, ensuring a wide safety margin. The key findings are:

i. The CO_2 will stay where it is put: Computer models show that the CO_2 will not spread far enough to reach any nearby natural fractures or old wells.
ii. The natural seals are very strong: The layers of sealing rock are highly effective. Research shows that natural chemical reactions could even improve the sealing capability over time.
iii. No significant earthquake risk: For the pilot phase, the pressure created by injection is too low to cause any noticeable seismic activity.

In summary, for this pilot phase, the study concludes that the storage operation is safe and does not pose a significant risk to human health or the environment.

4. Considerations for Future Larger-Scale Storage

The study confirms that the geological features ensuring safety for the pilot project also provide a reliable foundation for potential larger-scale operations. Safety is an integral part of the system's design, achieved through continuous monitoring and proper pressure management—standard practices in geological storage worldwide. This proven approach ensures that any future expansion would maintain the same high safety standards established for the pilot phase.

5. Commitment to Safety and Regulatory Compliance

This project is conducted under strict European and Spanish regulations, which require proving complete safety before any permit is granted. The goal is to help fight climate change in a safe and reliable way, while maintaining open and transparent dialogue with citizens and local authorities.

In short, this risk assessment uses scientific and technical evidence to demonstrate that the geological storage of CO_2 at the Lopín site can be conducted safely. This finding supports the use of this technology to manage unavoidable emissions from hard-to-abate industrial sectors, such as cement and chemical production, where few other alternatives exist. This makes it an essential component of a comprehensive climate strategy.

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Executive Summary

1. Introduction and Project Context

This report presents a comprehensive risk assessment for the geological storage of CO_2 at the Lopín pilot site within the Ebro Basin, Spain. The work, conducted under Work Package 5 (WP5) of the PilotSTRATEGY project in close collaboration with Work Packages 2, 3, 4, and 6, contributes directly to the project's overarching goal: to demonstrate the feasibility and safety of CO_2 geological storage in key European basins through early and continuous integration of risk management into decision-making.

The primary objective is to ensure that the proposed pilot storage operation meets the highest safety and performance standards, guaranteeing no significant risk of leakage or harm to human health or the environment, in full compliance with the EU CCS Directive (2009/31/EC) and Spanish Law 40/2010.

The assessment has been structured in two sequential phases:

- **Phase 1:** A preliminary analysis that directly informed the Pilot Implementation Plan.
- **Phase 2:** An updated evaluation incorporating detailed results from site characterization (WP2), reservoir and geomechanical modeling (WP3), and implementation planning (WP4).

Two main operational scenarios were analyzed: a **Pilot Scenario** (injection of 100,000 tonnes of CO_2) and an **Industrial Scenario** (injection of up to 13-23 Mt). The methodology combines probabilistic models—including Monte Carlo simulations and Bayesian Belief Networks (BBNs)—to quantify uncertainties and assess risks, providing a more robust and realistic framework than conventional deterministic analyses.

A central component of the WP5 methodology is the implementation of a **system reliability assessment framework**. This approach not only quantifies the likelihood of safe performance but also identifies and prioritises the uncertainties and system components that most strongly influence the overall risk profile. As such, the assessment directly supports evidence-based risk management and guides targeted data acquisition to reduce uncertainty in future development stages.

2. Site Overview and Geological Context

The Lopín site is located in the central part of the Ebro Basin. The primary storage reservoir is the Buntsandstein B1 Formation (Triassic), a fluvio-lacustrine sandstone unit located at approximately 1,760 m depth. The site benefits from a well-defined multi-barrier seal system providing layered containment:

- Primary Seal: Buntsandstein B2 unit and the Rané Formation (Röt facies).
- Local Seal: Muschelkalk M2 unit, a ~200 m thick sequence of evaporites.
- Regional Seal: Keuper facies, a thick (>400 m) sequence of claystones and evaporites forming a robust regional barrier.

The storage structure is a horst bounded by NW–SE trending normal faults. The injection point lies 400–600 m from the nearest fault, and the closest deep well (Lopín-1) is about 10 km away. Regional seismicity is low, and the current stress regime is extensional.

3. Key Findings from the Risk Assessment

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The risk assessment evaluated multiple potential leakage and integrity pathways, yielding the following main conclusions:

1. **Pilot Case (100,000 tonnes)**
   - Leakage via Existing Faults: Very low risk. The simulated CO_2 plume remains well confined and does not reach bounding faults.
   - Leakage via Abandoned Wells: Negligible risk. The plume does not extend to the nearest known well (Lopín-1, 10 km away).
   - Leakage through Seal Formation: Low risk.
     - Geochemically: Simulations indicate that the primary seal is chemically stable, with a tendency for self-sealing.
     - Geomechanically: The pressure increase (<2 MPa) remains far below the estimated fracture pressure.
   - Induced Seismicity: Low risk. The analysis shows a positive safety margin against fault reactivation.

2. **Industrial Case (up to 23 Mt)**
   - Plume Migration: The plume is expected to reach the bounding faults but remain trapped within the secondary containment system.
   - Pressure Buildup: This is the most critical factor. The probability of exceeding safe limits is highly sensitive to reservoir permeability, ranging from moderate-high (Base Case) to low (Best Case).
   - Induced Seismicity: Moderate but manageable risk. Combined pressure and thermal stress could reactivate small fractures near the wellbore, mitigable by CO_2 pre-heating.

4. Synthesis and Recommendations

The synthesis confirms that the Lopín site is highly suitable for pilot-scale CO_2 injection. All assessed scenarios show a low risk profile and compliance with regulatory safety standards.

For potential industrial-scale deployment, site viability depends on reducing key uncertainties. The following actions are prioritized:

1. Refine reservoir characterization: acquire additional data on porosity and permeability through a dedicated characterization well. This is the most critical action to constrain pressure predictions.
2. Adopt a phased, adaptive pressure management strategy: use the pilot phase as a large-scale “well test” to calibrate dynamic models. Define future injection rates based on real-time data rather than pre-injection assumptions.
3. Conduct targeted fault and geomechanical studies:
   - Determine the hydraulic behavior of the bounding faults.
   - Obtain site-specific geomechanical data to better constrain fracture pressure.
4. Evaluate thermal management options: perform a technical–economic assessment of CO_2 pre-heating as a means to mitigate thermally induced stress and seismicity.
5. Validate models with brine chemistry data: verify geochemical model predictions using the site’s native, high-salinity brine composition.

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5. Conclusion

The Lopín site presents a robust geological setting for CO_2 storage. This risk assessment provides a strong safety case for the pilot phase, demonstrating negligible likelihood of leakage or significant induced seismicity.

Moving toward industrial-scale operations will be guided by a structured, data-driven approach where continuous monitoring validates and refines our models. This adaptive process ensures that safety and performance are maintained throughout the project lifecycle. Geomechanical analyses reveal that fractures near the injection points exhibit high sensitivity to variations in pore pressure, underscoring the need for continuous fault monitoring.

The transition from pilot to full-scale storage is therefore a deliberate, evidence-based progression—ensuring long-term containment security while advancing the deployment of sustainable CO_2 management solutions.

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PilotSTRATEGY Project Work Packages (WPs)

This report summarises the results of Work Package 5 (WP5) of the European project PilotSTRATEGY. Throughout the document, reference is made to several work packages of the project, which are closely interconnected with the activities carried out in WP5. To assist the reader, a brief description of the purpose of each WP mentioned in the text is provided below.

- **WP1 – Coordination and Management:** Ensures overall project management, coordination between partners, and delivery of results.
- **WP2 – Geo-characterisation:** Develops the conceptual geological models of the pilot sites and provides the fundamental subsurface data for the subsequent WPs.
- **WP3 – Static and Dynamic Simulations:** Develops detailed numerical (static and dynamic) models of the storage system to predict CO_2 behaviour (plume migration, pressure evolution) and assess capacity. Its results are a key input for the implementation and risk assessment WPs.
- **WP4 – Pilot Development and Implementation Plans**: Integrates all technical, environmental, socioeconomic, financial, and regulatory aspects to define a feasible and robust pilot implementation plan.
- **WP5 – Safety and Performance (This report):** Provides the continuous risk assessment framework for the project. It is operational from the earliest stages, guiding decision-making in other WPs by identifying key uncertainties and evaluating the safety implications of site data, model results, and design options. Its iterative process ensures that risk management is integrated throughout the project lifecycle.
- **WP6 – Social Acceptance and Community Engagement:** Investigates social acceptance through proactive stakeholder dialogue, adapting the engagement strategy to regional contexts and technical project progress.
- **WP7 – Public Communication and Project Impact Management:** Manages external communication, dissemination, and maximisation of the project's impact.

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1. Introduction

1.1 Context and project background

The PilotSTRATEGY project aims to promote the development of safe, permanent, and socially acceptable CO_2 storage solutions in five European regions. The project focuses on the characterization, feasibility assessment, and preliminary design of storage complexes to support the future deployment of Carbon Capture, Utilization, and Storage (CCUS) infrastructure at a regional scale. Within this framework, the Ebro Basin in Spain has been selected as one of three priority regions for detailed site investigation and pre-Final Investment Decision (FID) preparation. The work is structured into interconnected work packages (WPs), each of which is briefly described at the beginning of this document.

A central tenet of the project is the integration of risk assessment into all stages of site development. Risk considerations are incorporated from the outset to inform decision-making and provide risk-based recommendations. This continuous, iterative approach ensures that uncertainties are systematically addressed and that safety and performance objectives remain fully aligned with the EU CCS Directive throughout the project lifecycle.

Work Package 5 (WP5) establishes the methodological foundation for this risk-based process and applies it to the detailed assessment of the Lopín storage site. This work integrates contributions from WP2 (site characterization), WP3 (reservoir simulation), WP4 (implementation planning), and WP6 (social perception) to evaluate the risks associated with long-term CO_2 storage. Task 5.1 provided the overall method for WP5. This report is a synthesis of all other activities in the WP (T5.2, T5.3, T5.4, T5.5 and T5.6) which collectively describes a complete risk management workflow. The resulting analyses support the identification of suitable pilot-scale options, inform regional-level decision-making, and contribute to preparing the site for future authorization and implementation stages.

1.2 Objectives and scope of the deliverable

This deliverable focuses on identifying, analyzing, and evaluating risks associated with the geological storage of CO_2 at the Lopín site. A cornerstone of the project's philosophy has been the **early and continuous integration of risk assessment** into decision-making. From the outset, the evolving risk model has actively informed other work packages, providing critical insights into uncertainties to guide key decisions at each project phase.

The study is structured in two sequential phases:

- A **preliminary first phase** that provided direct input for defining the "Pilot Implementation Plan".
- A **second phase** where all risk evaluations were updated with results from site characterization (WP2), detailed modeling (WP3), and implementation planning (WP4)

Two main operational scenarios were analyzed: a **pilot scenario** limited by current regulations to a maximum injection of 100,000 tonnes of CO_2, and an **industrial scenario** based on the site's estimated storage capacity. The assessment employed Monte Carlo simulations and Bayesian Belief Network models, considering different parameter sets and injection rates. The results identify critical factors for long-term storage security and highlight key uncertainties requiring further investigation.

1.3 Regulatory framework (EU Directive 2009/31/EC on CO_2 Storage and Guidance Document)

The primary regulatory framework for the geological storage of CO_2 in Spain is **Law 40/2010, of 29th December**, which transposes **EU Directive 2009/31/EC** of the European Parliament and of the Council. This law establishes the legal framework for the safe underground storage of CO_2 and is based on two main permits, granted by the Ministry for the Ecological Transition and the Demographic Challenge (MITERD), which require favourable reports from other competent authorities, including the Autonomous Communities.

- **Exploration Permit:** This permit is granted for the exploration of a specific area and confers the exclusive right to investigate. Its maximum validity is 6 years, with the possibility of a single extension of up to 3 years. Activities focus on characterizing the potential site to determine its suitability and safety.
- **Storage Permit:** This permit, granted for a specified duration, authorizes the operation of a storage complex and confers exclusive rights to its use. To obtain the permit, the applicant must demonstrate—through comprehensive site characterization—that the storage operation can be conducted safely and permanently, without posing significant risks of leakage or harm to human health or the environment. The application dossier must include, among other critical elements:
- A detailed **risk assessment** and a corresponding management plan.
- A **monitoring plan** compliant with the requirements of Annex II of the Directive.
- A **corrective measures plan** to manage any potential leaks.
- A **closure and post-closure plan**, ensuring long-term security after injection activities have ceased.

Furthermore, the regulations mandate the provision of financial security to cover all obligations arising from the permit, including the closure, post-closure phases, and potential corrective measures. The entire process is governed by the polluter pays principle.

1.4 Report structure

This deliverable is organised into six main sections, each addressing a specific aspect of the geological storage preliminary risk assessment. Following the introductory section, which outlines the project context, objectives, scope, and relevant regulatory framework (Section 1), Section 2 provides an overview of the regional geological context relevant for the risk identification and analysis.

Section 3 focuses on the Preliminary Risk Assessment and Pilot Implementation Plan, encompassing the initial identification of risks, a preliminary quantitative analysis (Phase 1), and the evaluation of outcomes for the pilot case. This section also summarises the results of sensitivity analyses and provides recommendations for subsequent modelling phases.

Section 4 presents the Risk Assessment Synthesis, which integrates updated data, refined modelling results, and the perception of stakeholders. This section analyses in detail the key risk scenarios, including potential leakages (through wells, faults, and seals) and induced seismicity.

Finally, Sections 5 and 6 include the recommendations derived from the overall risk assessment and the conclusions, respectively, highlighting the main findings and implications for the safe and efficient implementation of CO_2 storage at the selected pilot site.

2. Overview of regional context

This section defines the main characteristics of the storage site and establishes the basis for the risk assessment developed in the following chapters. The analysis focuses on the Normal Evolution Scenario, which represents the expected long-term behavior of the injected CO_2 within the storage complex, assuming that all system components perform according to design specifications and that the system is influenced only by the intended injection operations, without the action of external or unforeseen factors.

Within this framework, the regional and local characteristics of the site — including location, stratigraphic configuration, properties of the storage and sealing formations, presence of structural traps and faults, existing wells, natural seismicity, and hydrogeological regime — are described and analysed in terms of their relevance to the long-term safety and performance of the storage system.

The Normal Evolution Scenario provides a structured representation of the key physical, geochemical, hydrogeological, and geomechanical processes governing the fate of CO_2 in the subsurface, as well as the potential pathways through which fluids or pressure could migrate under normal operating conditions. These processes are grouped as follows (see Appendix 8.1.1 for further details):

- Plume and pressure dynamics: This component addresses the spatial and temporal evolution of the injected CO_2 and the associated pressure perturbation generated within the reservoir.
- Fluid–rock interactions: This component considers the geochemical and hydraulic interactions between the injected CO_2, the formation brine, and the rock matrix, which can influence the long-term integrity and performance of the storage system
- Potential migration pathways and leakage risks. This component identifies and characterizes potential pathways through which CO_2 or pressure perturbations could migrate beyond the intended storage volume
- Geomechanical response. This aspect addresses the mechanical effects of injection-induced pressure changes on the storage formation and surrounding units

2.1 Site location and geological setting

The study area is located near the southern edge of the Ebro Basin (Figure 1). Towards the central part of the Ebro Basin, the structure corresponds to a gentle syncline (Quirantes, 1978). This fold accommodated the slight reactivation of WNW-ESE basement faults originated at the Mesozoic extension (Arlegui and Simón, 2001).

The underlying basement is formed by Paleozoic rocks with some degree of metamorphism. Above the basement there are Triassic sediments including Buntsandstein, Muschelkalk dolostones, limestones, and evaporites and Keuper evaporites and shales (Figure 1). The oldest Jurassic rocks

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constitute of dolomites overlain by anhydrite unit bearing dolomitic interbeds (Lécera Fm) (Jurado, 1990; Gómez et al., 2007).

This sequence is overlaid by several carbonate sequences (dolomites, limestones and limestones with interbedded marls). This is overlaid by carbonate and detrital Cretaceous deposits. The base of the Cenozoic evaporitic and detrital rocks is unconformable. This erosional surface cuts the Cretaceous and Jurassic deposits

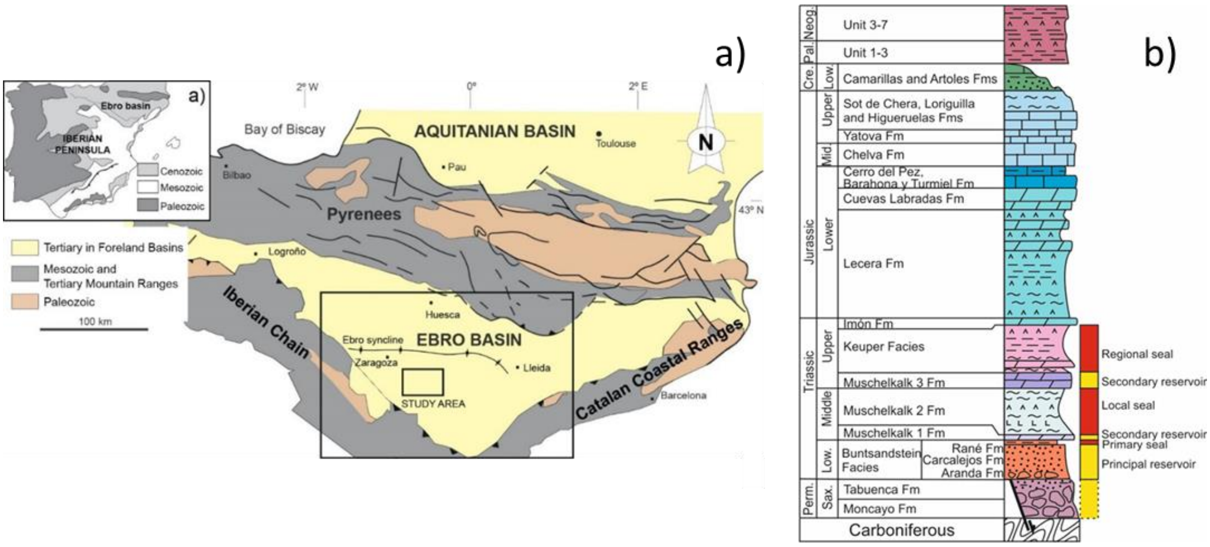

Figure 1: a) Geological sketch of the northeastern part of the Iberian Peninsula showing the study area in the central sector of the Ebro Basin and the Alpine ranges (Wilkinson, M. 2023, D2.7); and b) Simplified lithostratigraphic column of the area (Wilkinson, M. 2023, D2.7).

The Buntsandstein (main reservoir) contact with the Carboniferous is clear and slightly discordant. Arche et al. (2004) described three formations, from bottom to top, as shown in the Figure 1.

From legacy wells wireline logs this project has split the Buntsandstein reservoir into three parts, from bottom to top: B1 (conglomerates, sandstones and thin silty/clay interbeds), B2 (a thick argillaceous / silty sequence with some sandstone intercalations) and B3 (approximately 30m of fine sediments with evaporites considered to be the primary seal).

From a structural point of view, Figure 2 shows the orientation of the normal faults, which delineate a series of three horsts and four grabens with the same orientation. The throw of the faults varies between few tens of meters to about 500 m.

In Figure 2 there is a basal succession of Paleozoic basement rocks, Buntsandstein facies and M1 dolostones affected by normal faults forming horsts and grabens. Above this, the Middle Triassic evaporites (M2) act as a decoupling level above which the normal faulting is not observed. The M2 is overlain by the M3 and Keuper facies together with the Jurasic-Cretaceous rocks. At the top of the profile, Cenozoic strata overlap an unconformity.

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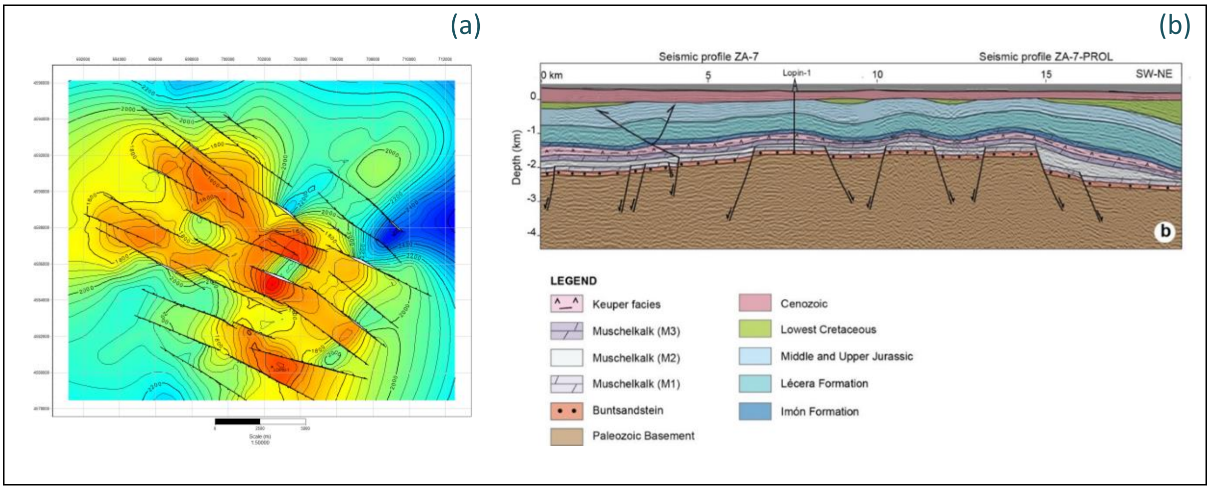

Figure 2: (a) Isobath map of the top of the basement (Paleozoic) rocks and NW-SE normal faults separating the horst and graben blocks; (b) Geological and structural interpretation on depth-converted seismic profiles without vertical exaggeration, including the projection of the Lopín-1 well (Wilkinson, 2023, D2.7).

2.2 Storage reservoir properties

Based on the evaluation of the lithostratigraphic units according to their role within the storage complex, the main storage can be assigned to the Lower Triassic Buntsandstein B1 facies (Aranda Fm.), at 1760 m below the surface, delimited by the Buntsandstein B2 formation (Carcalejos Fm.) capped by the Röt facies (Rane Fm.), which act as a primary seal.

The main reservoir is a fluvio-lacustrine formation in which the main sand channels drain to the northeast. Two facies have been identified:

- The Buntsandstein Conglomeratic facies, with a thickness that increases from 22 m to 35 m to the north. It consists mainly of conglomeratic channels interbedded with siltstones and sandstones. This formation lies directly above an erosional unconformity on the Paleozoic rocks.
- Buntsandstein B1, with a thickness that could increase from 20 m to 70 m to the northeast and is considered the thickness of the reservoir formation. It is composed of anastomosing fluvial channels. Compositionally, it is a subangular quartz arenite coated with Fe oxides Goethite type, quartzitic cement, and minor contents of feldspar and clay minerals. Laterally and vertically, it transitions to fine-grained red sandstone.

The total thickness of the Buntsandstein in the Ebro Basin is quite variable, from 17 to 532 m. Considering that the stratigraphic columns outside the basin, in Peñarroyas and Torre de las Arcas, show 118 m and 136 m of Buntsandstein respectively, the average thickness could be established at 127 m (Mathurin et al., 2023, D2.11).

The isobaths of the Buntsandstein Formation roof show the selected structure, whose probable containment closure is located at a depth of approximately 1650 m. The injection point elevation in the Aranda Unit of the Buntsandstein B1 Formation would be 1760 m above the surface.

The site also features two possible secondary reservoirs: one, the Muschelkalk M1 Formation, located above the Rané Formation in the Röt facies, above the Buntsandstein B2 Formation, already mentioned, and the other, the Muschelkalk M3 Formation. The Muschelkalk M2 Formation would act

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as a local seal above M1. Both the M1 and M3 facies of the Muschelkalk Formation are thick dolomitic formations with some intercalations of anhydrites or salts and/or marls/limestones.

Muschelkalk M1 is affected by the same structures and deformation style as Buntsandstein. It is covered by a seal of clays and anhydrites, Muschelkalk 2 (M2), whose thickness ranges from 17 to 323 m. M1 and M2 are present in the Ebro Basin at depths from 590 m (Caspe-1 well) to 3,250 m. Muschelkalk M1 and M2 are part of the deep Triassic hydrogeological system and do not outcrop within the basin.

2.3 Caprock / Seal description

Three types of seals are distinguished: a primary seal (Buntsandstein Formation B2 with the Rané Formation in the Röt facies, above), a local seal (Muschelkalk M2), and a regional seal in the Keuper facies. The latter is accepted as the regional seal for the Lopín site storage complex.

The Buntsandstein B2 Unit, or Carcalejo Formation, of the primary seal represents isolated fluvial systems in a floodplain. It is a highly clayey formation with sandstone interbeds that overlies the main storage level (Buntsandstein B1). The thickness of Unit B2 varies between 56 and 76 m, increasing towards the center of the basin, and its porosity varies (on average) from 2.11% to 14.11% in the Ballobar-1 and Caspe-1 boreholes, respectively.

At the top of Unit B2 lies the Rané Formation (Röt facies), a supratidal sedimentary deposit typical of arid coasts, characterized by carbonate-evaporite deposits with some siliciclastic rocks, a transition to a sabkha facies. It consists of alternating layers of fine-grained red mudstones and sandstones with interbedded very fine- to fine-grained sandstones, mudstones, and siltstones. The thickness of individual layers varies from 5 to 10 cm. The clay content (V_{sh}%) ranges from 67.1 to 87.0%, and the effective porosity from 0.67% to 2.77%.

This formation was initially considered the primary seal of the storage complex, but its dubious effectiveness due to both its lithology and its sedimentary discontinuity suggests taking this level as an intermediate seal that could play a relevant role, not without uncertainties, in the behavior of the evolution of the CO_2 plume in the injection phase.

The local seal Muschelkalk 2 (M2) is a succession of Middle Triassic evaporites and shales, ranging in thickness from 17 to 323 m in the Ebro Basin. At the Lopín-1 well, it is 200 m thick. This formation is composed of anhydrites, salts, and shales. The Middle Triassic evaporites (M2) exhibit significant lateral variations in thickness and act as a decoupling zone above which normal faulting is not observed. The grain size ranges from medium to coarse sand, composed of monocrystalline quartz and abundant muscovite. No values for V_{sh}, effective porosity, or hydraulic conductivity were obtained analytically. Muschelkalk M2 is attributed with the hydrogeological behavior of an aquiclude (Mathurin et al. 2023, D2.11).

Finally, the site exhibits a regional seal in the Upper Triassic in the Keuper facies. The Keuper facies is characterized by the presence of three units: a lower evaporitic unit (K-1), formed by halite with mudstone and anhydrite intercalations, an intermediate mudstone unit (K-2), and an upper evaporitic unit (K-3), consisting of anhydrite (Jurado, 1990).

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This Keuper facies can be considered a regional seal due to its extent and thickness in the Ebro Basin. Keuper layers reach thicknesses exceeding 500 m. In the description of the Lopín-1 borehole (Lanaja, 1987) the Keuper is attributed thicknesses of approximately 445 m, between 905 and 1350 m depth on the order of the maximum value estimated in the Ebro Basin. In the deliverable 2.7 (Wilkinson, 2023), it is attributed a succession of up to 400 m thick of continental evaporites and fine clastic rocks of Late Triassic age (facies de Keuper) (Jurado, 1990; Ortí et al., 2017).

The overburden above the regional sealing level (Keuper), whose base would be 1300 m deep with respect to the surface elevation (-1050 m a.s.l.), is made up of 670 m of Jurassic materials and 230 m of Cenozoic materials, totaling 900 m.

2.4 Structural/Stratigraphic traps and fault framework

The storage complex structure is a structural high that forms part of the pre-Alpine basement of the Ebro Basin. The trap is a basement horst parallel to the northern margin of the Iberian Range (NW-SE), a structure bounded by normal faults (NW-SE direction and steep dip (>60º)) that affect, in addition to Paleozoic materials, the Buntsandstein and the Muschelkalk M1 (Wilkinson, 2023, D2.7). It can be concluded that all the faults have a steep dip and a short length, generally around 300 m or less. The degree of lateral sealing of the normal faults is under evaluation, although the pressure data from the Drill Stem Test (DST) in the well already suggest that they could partially seal the Buntsandstein B1, especially in the center of the basin.

These normal faults have dips such that, in both directions of the possible migration of the CO_2 plume, it would encounter a fault plane arrangement of the type described by Chang and Bryant (2007) as "declined". Given that these are presumably permeable normal faults, CO_2 displacement would likely be rapid due to the potentially higher permeability of these faults. It is doubtful that the permeability level of these faults was influenced by subsequent compressive repetition during the Alpine orogeny. Assuming these faults are permeable, which is the most conservative hypothesis for risk assessment purposes, CO_2 migration would occur primarily along the fault plane, upwards towards the contact between the B1/B2 reservoir formation and the M2 Muschelkalk sealing formation (anhydrites, salts, and shales), and secondarily across the fault plane.

If these faults also cross the local M2 seal (a conservative assumption to maximize risk), CO_2 would reach the Muschelkalk M3. Since this is bounded at the top by the Keuper, which is about 400 m thick and has very low permeability, preferential migration would be in the direction of the dip of the M3 level.

At the Lopín site, in addition to the NW-SE trending normal faults (the closest of which are located approximately 600 m north and 400 m south of the injection point), a system of reverse faults has been identified affecting the Mesozoic deposits overlying the Muschelkalk M2 evaporite facies (local seal). These faults are potentially impermeable, having originated from the compressive forces of the Alpine orogeny. They cut through the regional seal in the Keuper facies, although they are fossilized by the Neogene materials of the Tertiary cover, as an erosional unconformity, at a depth of approximately 300 m. The first system of reverse faults appears southwest of the current Lopín-1 borehole, about 6 km away from the current injection site (Bouquet, 2024; Chassagne, 2024; Deliverable D3.4, 2025).

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2.5 Legacy wells and man-made features

Regarding the deep wells present in the area, a total of 13 have been identified (Figure 3), the closest to the injection well being Lopín-1, at about 10 km. This penetrates the Buntsandstein formation 32 m from the top. The rest of the wells are located more than 20 km northeast or southeast of the injection well, with no known wells west of the area of interest, except for the Zuera-1 well located more than 48 km to the NW.

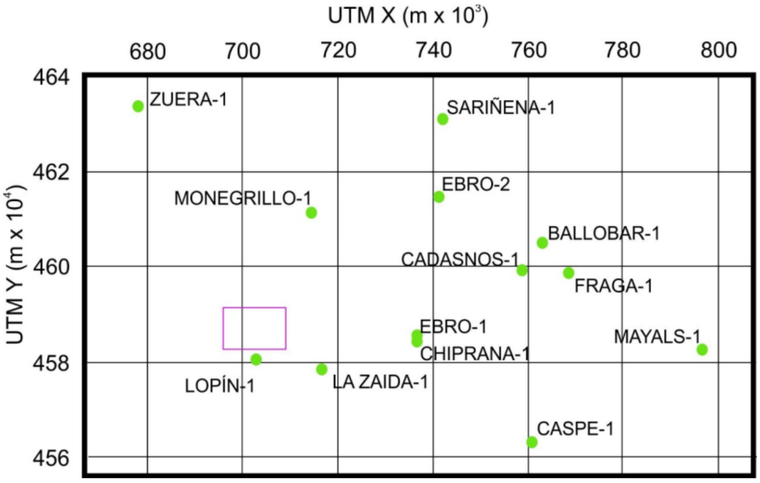

Figure 3: Location map of the deep wells considered in the Lopín area (Wilkinson, M. 2023)

In general, the area has a low population density, with small towns and a large percentage of agricultural land without urban centres.

2.6 Environmental context

Above the top of the Keuper, at a depth of 905 m in the Lopín-1 well column (Lanaja, 1987), lie anhydrites and dolomites of the Infra-Lias, dolomicrites and dolomicrosparites of the Lower Lias, limestones and marly limestones of the Middle and Upper Lias, Dogger limestones, and Oxfordian and Kimmer limestones of the Upper Jurassic. A total of 670 m of calcareous materials plus 230 m of clayey and gypsum materials of the Tertiary, representing a thickness of approximately 900 m from the top of the regional seal to the surface.

The Imón and Lécera formations, the Lower and Middle Jurassic dolomites and the Upper Jurassic anhydrites (Dogger) are fossilized by Neogene materials in an erosional unconformity about 300 m from the surface (Figure 2).

Taking the lithostratigraphic column of the Lopín-1 well as a reference for the injection well, the overburden, formed by materials from the Lower Lias, Upper Lias and Upper Jurassic materials, shows the hydrogeological behavior of a heterogeneous aquifer of multiple layers with secondary porosity due to fracturing in the limestones and dolomites, and aquifers in the Lower Jurassic (Lécera Formation) and Upper Jurassic (Malm) levels. The Imón Formation, at the top of the regional seal in Keuper facies, shows aquifer behavior. The undifferentiated clayey and gypsum materials of the Tertiary would be an alternation of medium to low permeability layers with aquitard behavior (Figure 4).

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The Jurassic aquifer system consists of two confined aquifers: a lower (Liassic) aquifer composed of 300 m thick carbonate formations and a Middle-Upper Jurassic (Dogger-Malm) aquifer, also composed of 80 m thick carbonate formations, separated vertically by 300 m of marly-anhydrite formations. The upper boundary of the Jurassic aquifer is the reddish gypsum clay of the Paleogene, which acts as the confining formation (Mathurin et al., 2023, D2.11) (Figure 5).

The Lower Lias aquifer exhibits the best hydraulic properties, with transmissivities up to 1000 m²/day and extraction rates of 100 L/s. The storage coefficient is estimated at $5·10^{-5}$ (IGME-DGA, 2009; IGME-DGA, 2010). The Upper Malm-Dogger aquifer shows lower values, with average transmissivities of only 38 m²/day (IGME-DGA, 2009; IGME-DGA, 2010; Mathurin et al., 2023, D2.11).

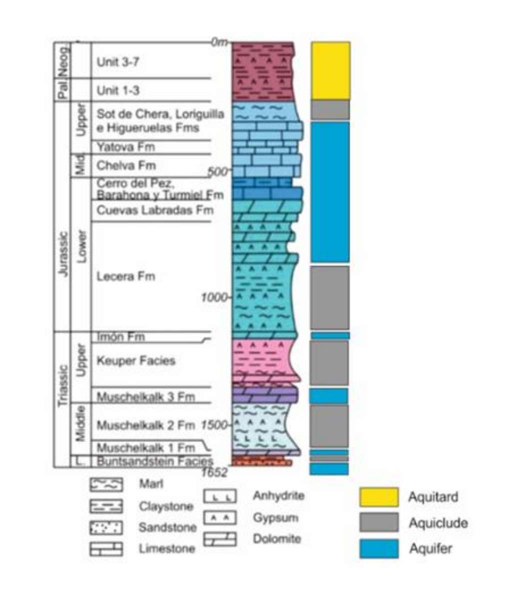

Figure 4: Synthesis of aquifer, semi-permeable, and impermeable levels (from Mathurin et al., 2023, D2.11).

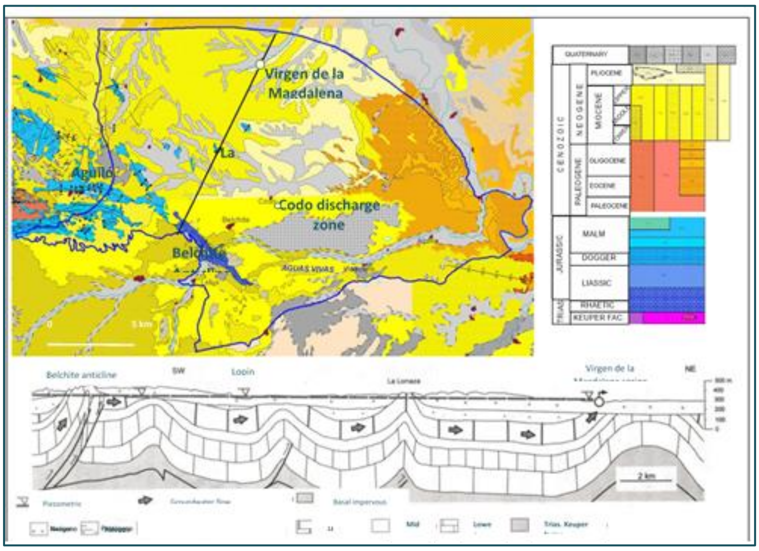

Figure 5: Conceptual model of the Upper Jurassic aquifer flow along a NE–SW cross-section. The main recharge area is located to the SW (Belchite Anticline), where the Lower Liassic and Upper (Dogger–Malm) aquifers are hydraulically connected through faults. The main discharge area corresponds to the Virgen de la Magdalena spring at the northern end (from Mathurin et al., 2023, D2.11).

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Recharge occurs through direct infiltration of rain and snow, infiltration from the Ebro riverbed, and lateral recharge of groundwater from surrounding formations, the Sierra Ibérica to the south and the Pyrenees to the north (Mathurin et al., 2023).

There are some discharge zones associated with the Middle-Upper Jurassic regional aquifer, such as the La Virgen de la Magdalena spring, located in Mediana de Aragón, with an average flow rate of 125 L/s. The lower aquifer, from the Lias (Lower Jurassic), only outcrops in the Belchite anticline, 10 km south of the Lopín structure. Both natural discharge zones would be of potential interest for environmental risk assessment within the context of the normal development scenario of the storage complex in the Lopín structure (Figure 5).

The only identified regional discharge zone is located 90 km northeast, near the city of Lleida, and only affects the upper aquifer system (Jurassic and Cenozoic), not the deep Triassic aquifer system, where the CO_2 injection would take place [Mathurin et al., 2023. D2.11).

Surficial zone

The site is located within the Ebro Depression, an arid and sparsely populated region in northeastern Spain. The main urban center is the municipality of Quinto, with an approximate population of 1,869 inhabitants (INE, 2023) and an area of 118.40 km².

According to the Köppen climate classification, the area has a cold semi-arid climate (type BSk). Winters are mild, with occasional nighttime frosts, and average maximum temperatures around 10°C. Fog and temperature inversions are common in December and January. Summers are hot, with maximum temperatures often exceeding 30°C, frequently surpassing 35°C, and even reaching 40°C during some heat waves. Minimum temperatures generally remain below 20°C, but tropical nights can occasionally occur. The prevailing winds are the cierzo (cold and dry, from the northwest) and the bochorno (warm and humid, from the east). The cierzo wind can be strong year-round, especially between October and April. Rainfall is scarce, with annual totals barely exceeding 300 mm. Precipitation is concentrated mainly in spring and autumn, while winters and summers are dry. This area corresponds to an impermeable surface mainly occupied by tertiary materials.

Regarding surface water resources:

- There are no surface aquifers in the area.
- Groundwater is found at great depths.
- The Ebro River is the main source of water for human consumption and agriculture.

Natural Seismicity and Tectonic Stress Regime

The Ebro Basin, where the Lopín structure is located, is characterised by relatively low seismic activity (Olaiz et al., 2024, D2.5). Historical records from the Spanish National Geographic Institute (IGN) date back to 1371, with the first documented earthquake in the study area occurring in Ribagorça (Lleida) in 1373, reaching an estimated intensity of VIII–IX on the European Macroseismic Scale (EMS-98). The Iberian Peninsula is mainly affected by a strike-slip tectonic regime, with a maximum horizontal stress (S_{Hmax}) oriented NW–SE, which has remained nearly constant since the Late Miocene. According to the World Stress Map (Heidbach et al., 2016), the S_{Hmax} direction in the Ebro Basin is consistent with regional trends showing a clockwise rotation from NW–SE to NNW–SSE across Iberia. In the

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northeastern sector, including the Ebro Basin, stress trajectories bend towards N–S and NE–SW, coexisting with extensional domains such as the Iberian Range and the Valencia Trough.

The Lopín site lies within the Ebro Depression, close to the foothills of the Iberian Range, and is affected by two main fault systems. The first consists of high-angle normal faults that delimit horst and graben structures, shaping the Buntsandstein formations (B1 and B2), the Röt facies (primary seal), and the Muschelkalk M1 (possible secondary reservoir), which are related to Mesozoic extensional tectonics. The second set includes reverse faults associated with Alpine compression, affecting overlying Mesozoic deposits above the Muschelkalk M2 evaporitic facies (local seal). Since the Late Miocene, the stress regime has been predominantly extensional, related to NW–SE faults with Quaternary activity in the Iberian Range. Consequently, during CO_2 injection under such extensional conditions, only faults located in overlying or underlying formations are likely to be reactivated, whereas in compressional settings the most probable reactivation would occur within the reservoir itself.

3. Preliminary Risk Assessment and Pilot Implementation Plan

This section synthesizes the results of the first round of risk assessment conducted under Work Package 5 (WP5) of the PilotSTRATEGY project and outlines the key preliminary decisions for the pilot implementation (WP4), which will form the basis for the second assessment round.

The initial risk assessment followed a structured three-phase methodology: risk identification, risk analysis, and risk evaluation, culminating in a set of recommendations for Phase 2 detailed in a dedicated decision-analysis section.

The studies focused on the Lopín site in the Ebro Basin, evaluating two primary scenarios aligned with WP4 objectives:

- **Pilot Scenario:** Limited by current regulations (transposing Directive 2009/31/CE into Spanish law via Law 40/2010) to a maximum injection of 100,000 tonnes of CO_2.
- **Industrial Scenario:** Defined by the site's estimated storage capacity of approximately 13 Mt, considering injection rates of 11 kg/s (0.35 Mt/yr) and 20 kg/s (0.63 Mt/yr).

This first-phase assessment focused on the injection period, as it represents the phase of highest risk for geological CO_2 storage. Injection-induced pore pressure increase can reactivate fractures and trigger seismic activity, while the processes leading to permanent CO_2 trapping (e.g., dissolution, mineralization) have not yet had sufficient time to act.

The assessment employed probabilistic models, specifically Monte Carlo simulations and a Bayesian Belief Network (BBN), applied to the parameter sets derived from WP2. The BBN was designed *ad hoc* for the site's specific geological conditions and identified risks. Its structure and the probabilistic data feeding it were built from site characterization, integrating available information to represent the system's cause-effect relationships and quantify the associated uncertainty. This provides a decision-support tool capable of combining quantitative and qualitative evidence to evaluate how this uncertainty propagates into operational and long-term risks.

The network's behavior was first validated against qualitative calculations from the initial site selection methodology (Hurtado et al., 2014). It was then enriched by incorporating results from quantitative simulations of CO_2 plume migration and pressure front evolution during injection, alongside specific

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sub-models to quantify leakage probability through the main identified pathways: fractures/faults and abandoned wells. The final application of the BBN generates probability distribution functions for risk, both for the overall storage system and its individual subsystems: storage and primary seal, secondary containment, and near-surface dispersion.

The system's primary perturbations are related to CO_2 plume migration and induced overpressure. Plume morphology, its extent within the reservoir, and the overpressure distribution are the key initial factors determining the risk of CO_2 leakage from the storage formation. Both aspects can be modeled using analytical or semi-analytical approaches, facilitating their use in preliminary risk assessments. The following sections detail the specific models used in this study.

3.1 Initial risk identification

The scenarios were identified through a systematic expert elicitation process based on meetings held with the Ebro team. The results of the meetings were cross-checked against established lists of Features, Events and Processes (FEP) (Quintessa, 2014) relevant to the storage systems, and they were compared with the risk scenarios and uncertainties identified in other projects. The work produced a small number of scenarios that broadly represent the main types of risks that could occur. Subsequently, for each scenario the following aspects were addressed:

- The identification of plausible temporal and spatial leak patterns.
- Understanding the mechanisms by which these scenarios could occur.
- The determination of the environmental impacts associated with each of these scenarios.

During the scenario identification process, a small number of broadly representative and meaningful scenarios of the major types of impacts that could occur were developed. This identification also included those that may be particularly unlikely to occur (even if a leak does occur), and which can therefore be "discarded" in subsequent analyses. They are listed below:

EVOLUTION SCENARIOS

- Leakage through wells:
  - Leakage from an operating well
  - Leakage from an abandoned well
- Leakage through seal formation:
  - Through fracturing of the caprock due to over-pressurization ⇒ Loss of mechanical integrity of the caprock, potentially leading to migration risk scenarios:
    - Local over-pressurisation around the injection well
    - Reservoir over-pressurisation (regional scale)
  - Due to sealing deficiency of the caprock:
    - Via a higher permeable zone (diffusive leakage due to the presence of an undetected high permeability zone).
    - Via discontinuities (fractures, faults) in the caprock.
- Leakage via existing faults
- Exceeding expected lateral extent (CO_2):
  - Unexpected leak paths
  - Interaction with other resources

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- Migration of formation brine outside expected boundaries. Increased displacement of high salinity formation:
  - Interaction with other resources
- CO_2 accumulation in a secondary reservoir due to unexpected vertical migration.

PERTURBATIVE SCENARIOS

- Leakage due to seismic events (natural or induced). Induced seismicity can cause loss of mechanical integrity in the reservoir and other subsurface structures (especially in wells).
  - Fracturing, fault creation/reactivation
  - Loss of well containment
- Disruption by a later activity.
- Flow alterations: Changes in groundwater flow, within the reservoir or in other layers of the storage complex.

PERFORMANCE SCENARIOS

- Loss of Injectivity.
  - Reduced injectivity due to chemical changes / reactivity:
    - Reduced porosity due to chemical precipitation
    - Physical changes due to chemical reactions
- Lower than expected capacity
- Reservoir pressurization due to unexpected compartmentalisation
- Accidental Over-fill

3.2 Preliminary risk analysis (Phase 1)

This preliminary risk analysis focused on assessing the system's behavior under Normal Evolution Scenario conditions, which reflect the expected performance of the storage complex in the absence of external influences beyond the normal processes associated with CO_2 injection.

The Phase 1 analysis is based on Monte Carlo simulations to probabilistically characterize the processes linked to CO_2 injection and system pressure evolution. The simplified models and key input data are detailed in Sections 3.2.1 and 3.2.2.

The results from these simulations were subsequently integrated as "Soft Evidence" into the full Bayesian Belief Network (BBN) model. This approach enables a global and interdependent risk evaluation, as the BBN incorporates the main clusters associated with plume migration mechanisms, pressure evolution, and potential leakage through existing fractures, faults, or wellbores.

3.2.1 Key data and assumptions

The primary characteristics of the B1, B2, and Röt/Rané (B3) units were obtained from the Ebro-1 and Ebro-2 wells. These wells provide higher quality data and depths most "similar" to the proposed site, making them the best available representatives for the formation's properties.

3.2.1.1 Storage Formation Parameters

The following reservoir formation parameters, obtained from experimental data, were used in the analysis.

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3.2.1.1.1 Porosity-Permeability

Probabilistic risk assessments utilized Probability Density Functions (PDFs) for reservoir porosity and permeability. These PDFs were derived from laboratory data provided by IGME (Bouquet, 2024), considering exclusively intervals within the formation with porosities above 8%, as these represent the preferential flow zones.

Given the limited number of samples, two scenarios were evaluated to quantify the uncertainty in the distribution fitting:

- **Base Case:** The PDFs were fitted directly to the experimental data, assuming a normal distribution for porosity and a log-normal distribution for permeability. (Table 1).

Table 1: Porosity and permeability statistics for the Base Case

POROSITY (%)	PERMEABILITY (mD)
Normal (m=12,3914; s=2,97409) Mean: 12,3914 Standard deviation: 2,97409 Median: 12,3914 Mode: 12,3914	LogNormal(m=2.16631; s=2.56287) Mean: 232,86557 Standard deviation: 6209,9620 Median: 8,7260 Mode: 0,01225

- **Best Case:** To create a more robust fit and mitigate the impact of the small sample size, a synthetic population of 100 data pairs was generated from the experimental values using statistical bootstrapping. The PDFs for this case were fitted from this expanded population, providing a more stable estimate of the distribution parameters (Table 2). The "Best Case" establishes a theoretical upper limit on system performance, providing a benchmark for evaluating the potential benefit of future characterisation campaigns

Table 2: Porosity and permeability statistics for the Best Case

POROSITY (%)	PERMEABILITY (mD)
Normal (m = 15,2883; s = 3,01614) Mean: 15,2883 Standard deviation: 3,01614 Median: 15,2883 Mode: 15,2883	Lognormal(m=5.13135; s=2.06709) Mean: 1433,3656 Standard deviation: 12054,4733 Median: 169,2454 Mode: 2,3596

Risk evaluations were performed using both available PDF sets. A comparison between them is shown in Figure 6.

3.2.1.1.2 Storage Formation Thickness

The total thickness of the Buntsandstein formation in the Ebro Basin is highly variable, with a documented range of 17 to 532 meters. To establish a representative reference thickness for the study area, the stratigraphic columns of Peñarroyas and Torre de las Arcas, located on the basin margin with thicknesses of 118 m and 136 m respectively, were considered. Based on this, a mean thickness of 127 m was adopted for the models (Mathurin et al., 2023. D2.11).

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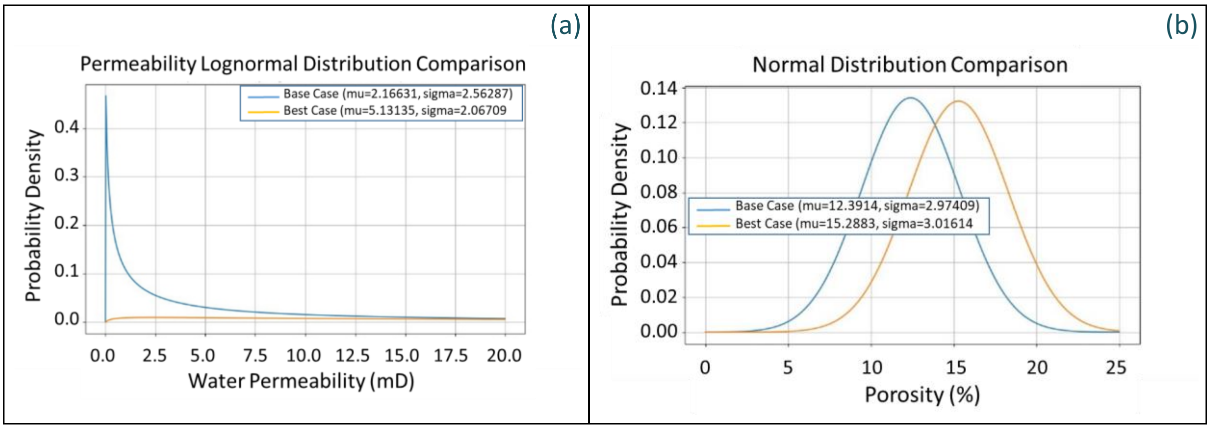

Figure 6: (a) comparison of the permeability PDFs for the base and best cases; (b) comparison of the porosity PDFs for the base and best cases.

For petrophysical characterization, this study used the permeability and porosity data defined in WP2. To focus the analysis on zones with the highest storage and flow capacity, only those intervals of the Buntsandstein formation with porosities greater than 8% were selected.

Ebro-1	B1			Ebro-2	B1	
Net Thickness	Total thickness	NtG		Net Thickness	Total thickness	NtG
87,95	140,62	62,55%		80,81	136,95	59,00%

3.2.1.1.3 Hydrogeological Gradient

From a risk analysis perspective, the initial hydrostatic pressure in the storage formation is a critical parameter. The injection of CO_2 will induce additional pressure buildup, creating a potential for hazardous overpressure scenarios. The hydraulic gradient, fitted using available experimental data from the Monegrillo-1, Chiprana-1, and Ebro-1 wells (located 32.85 km to 34.28 km away), is shown in Figure 7.

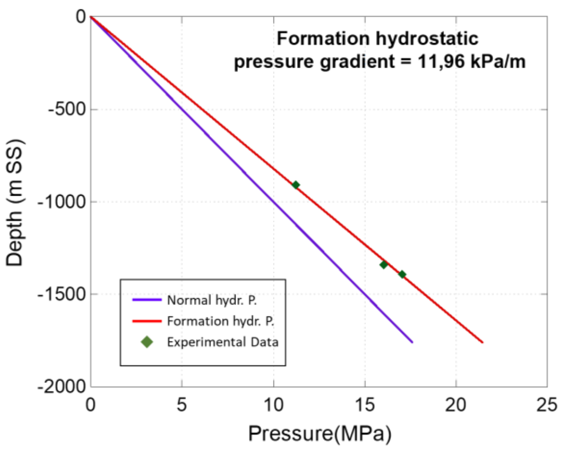

Figure 7: Hydraulic pressure at the top of the Buntsandstein formation. The experimental data correspond to the Monegrillo-1, Chiprana-1, and Ebro-1 wells, located between 32.85 km (Monegrillo-1) and 34.28 km (Ebro-1).

Critically, the experimental data confirm the presence of a pre-existing, natural overpressure condition within the Buntsandstein formation. This initial state significantly elevates the risk of

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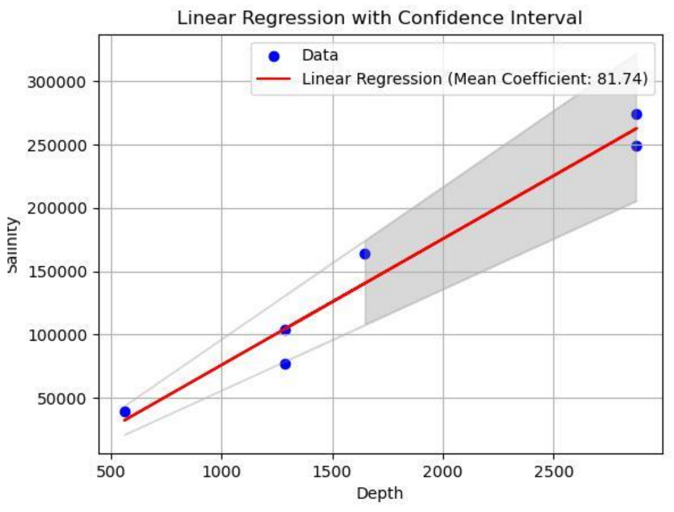
exceeding the mechanical strength of the primary seal, the Rané Formation (Röt facies). This risk is further exacerbated by the low permeability anticipated in the injection unit (Aranda Unit, Buntsandstein B1 formation at -1760 m.a.s.l.), which will hinder the dissipation of the injection-induced pressure, leading to a more pronounced pressure accumulation and drastically reducing the injection rates and maximum capacity.

3.2.1.1.4 Salinity

The salinity of the Buntsandstein aquifer is derived from nearby oil wells, which show salinities above 65,000 ppm NaCl, classifying them as deep brines. The available data, represented in Figure 8, reveal a clear positive correlation between salinity and depth. The fitting model derived from this correlation, also included in the figure, allows for the projection of salinity at the injection well depth. According to this model, the 95% confidence interval for the salinity range is between 113,600 and 183,400 ppm.

(a)



(b)

Bootstrap, with uncertainty: salinity = Interception + Coefficient*Depth
Interception: -23821,9883
Mean Coefficient: 81,7426
Standard deviation of coefficient: 354,8170
95% confidence interval for the coefficient: [79,9313 - 120,4642]

Figure 8: Salinity data versus depth with linear regression adjustment and a 95% confidence interval.

3.2.1.1.5 Temperature

The mean surface temperature in the Lopín area is 15 °C. The temperature gradient was obtained from the most representative wells, as shown in Table 3.

Table 3: Temperature gradients in the wells most representative of conditions in Lopín

Well	Temp. Gradient (°C/Km)
EBRO-2	31,6
EBRO-1	30,5
LOPÍN-1	29,2

Using these data, the mean temperature gradient is 30.4 °C/km.

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3.2.2 Modelling approach. Analytical models

Within the framework of geological CO_2 storage, the injection phase is identified as the period of highest leakage risk. During this stage, CO_2 remains as a separate mobile phase and system pressures reach their maximum values. Consequently, this phase is considered critical for risk assessment (Hurtado et al., 2021). The main risk factors during this phase are: (1) the extent of the CO_2 plume; (2) the distribution of induced overpressures within the storage formation; and (3) the temperature front generated when injecting CO_2 at a temperature different from that of the formation, which may influence the mechanical behavior of faults present at the site (phase 2). For preliminary assessments, these factors can be efficiently modelled using analytical or semi-analytical approaches. The following section presents the main characteristics of the models applied in this study.

3.2.2.1 Plume Evolution and Extent

The temporal evolution of the CO_2 plume is modelled for both the injection and post-injection phases, with the objective of characterising its long-term behaviour (Phase 2). The final extent of the plume is a critical parameter in risk assessment, as it enables the estimation of the probability of interaction with potential leakage pathways, such as abandoned wells or faults present at the site.

The following sections provide a detailed description of the analytical and semi-analytical models applied for this purpose.

3.2.2.1.1 Injection phase

During CO_2 injection, the displacement is due to a drainage process in which the non-wetting fluid - CO_2 - displaces the connate brackish fluid. This displacement leaves the brackish fluid connate at residual saturation in the biphasic zone.

In order to be able to perform MonteCarlo simulations and take into account uncertainties, risk analyses will make use of analytical (Nordbotten y Celia 2006a) or semi-analytical (Houseworth 2012) approaches capable of reflecting the global-scale behavior of CO_2. In both cases, the injection and subsequent migration of the free CO_2 phase in a deep brackish aquifer will be governed by the balance between buoyancy and viscous dispersion (Hesse et al., 2006). The gravitational number, which quantifies the ratio between gravitational and viscous forces (Kumar, 2008), is defined by Equation (1). This parameter provides the basis for comparing the applicability and scope of the two approaches.

$$\Gamma = \frac{2 \cdot \pi \cdot \Delta\rho \cdot g \cdot \lambda_w \cdot k \cdot B^2}{Q_{well}} \qquad (1)$$

where $\Delta\rho$ is the density difference [ML^{-3}]; g is the acceleration due to gravity [LT^{-2}]; λ_w is the mobility of water as the ratio of its relative permeability to the fluid viscosity ($\lambda_w = k_{rw}/\mu_w$); k is the intrinsic permeability [L^2]; B is the total formation thickness [L]; and Q_{well} is the volumetric injection rate [L^3T^{-1}].

The CO_2 plume evolution, illustrated in Figure 9, is defined by the following fundamental assumptions, common to both models:

i. CO_2 injection through a single well into a flat aquifer, horizontally homogeneous and confined at the top and bottom by impermeable layers. Also, the vertical equilibrium condition is considered, which is appropriate for systems where the vertical scale is much smaller than the horizontal scale. Under these conditions, the aquifer can be considered horizontal during the

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injection period since as the horizontal scale is much larger than the vertical it is appropriate to assume that the flow is essentially horizontal.

ii. It is assumed that the problem has a radial symmetry. It has been proven that radial symmetry is maintained even with perturbations such as the inclusion of an abandoned leaking well into the domain. The problem is limited to cases where the aquifer can be taken as horizontal and where other flow effects, such as regional groundwater flow, are small enough that the displacement pattern around the well is radially symmetric.

iii. A "sharp interface" approximation is adopted, assuming a well-defined separation between the CO_2 phase and the connate brine, and that the fluids fully occupy the pore space (S_{CO2} + S_w = 1).

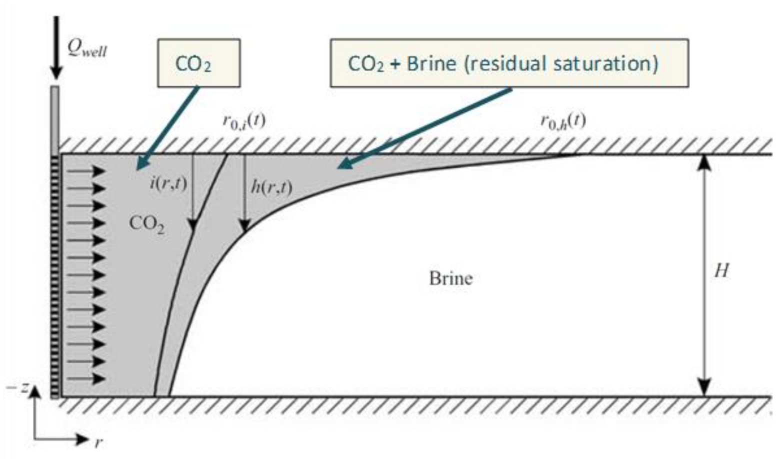

Figure 9: Diagram showing a typical CO_2 plume (Nordbotten and Celia 2006b): The CO_2 thickness is denoted by h(r, t), and the drying front is denoted by i(r, t).

The two approaches considered are:

a) **NORDBOTTEN:** A solution for the case where buoyancy acts to separate the fluids but plays no other significant role (Nordbotten and Celia 2006a).

Its application is appropriate in cases where buoyancy effects can be neglected, so that the solution is obtained under the assumption that $\Gamma \rightarrow 0$. These situations correspond to industrial-scale injection scenarios and cases with relatively high injection rates, low permeability, and/or thin aquifers, in which the governing equation reduces to a first-order differential equation. From a practical perspective, a value of Γ =0.5 can be adopted as a reasonable threshold, beyond which buoyancy effects should no longer be neglected. The approximations developed for plume evolution during the injection period also make it possible to determine the dry-out front that forms in the vicinity of the injection well.

The solution is valid for values of $\lambda \geq 1$ (eq. (2))

$$\lambda = \frac{\mu_w}{k_w}\frac{k_{nr}}{\mu_{nr}} = \frac{1}{Mobility\ ratio} \qquad (2)$$

Assuming Γ=0, an explicit expression for the plume advance front *h(r,t)* and the drying front *i(r,t)* can be obtained (Nordbotten and Celia 2006b)

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b) **HOUSEWORTH:** It derives semi-analytic expressions that reproduce the self-similarity solutions of the sharp interface equations quite accurately in the entire parameter space (Γ, λ).

For cases where Γ >0.5 and therefore buoyancy cannot be neglected, this parameter cannot be simplified in the expressions describing plume advancement. This leads to the impossibility of obtaining a fully analytical expression. In such cases, the plume evolution is determined using the Houseworth approximation (Houseworth, 2012), which reproduces with high accuracy the self-similar solutions of the sharp-interface equations across the entire parameter space (Γ, λ)

It has been verified that the set of solutions obtained agrees well with the numerical solution throughout the full parameter space.

3.2.2.1.2 Post-Injection Phase

A precise modelling of CO_2 plume evolution after the cessation of CO_2 injection is essential for risk assessment, as it enables the determination of its maximum extent and, consequently, the spatial domain that could potentially interact with leakage pathways. The analytical approaches applied provide a conservative framework, as they do not account for natural processes that reduce the mobility and impact of the injected CO_2. The most relevant mechanisms not included are:

i. Residual saturation trapping, which immobilises a fraction of CO_2 within the storage formation;
ii. Dissolution in connate brine, transferring CO_2 from the mobile to the aqueous phase;
iii. Viscous fingering instabilities, which slow lateral migration and enhance long-term stability;
iv. Stratigraphic heterogeneity (multilayered systems), which may compartmentalise flow and restrict gas movement.

Two approaches have been applied, both considered suitable for the hydrogeological context of the Ebro Basin, characterised by its horizontal geometry and very long residence time:

a) Effective Thickness Model (h_{eff}) (Fominykh et al., 2023; Zapata et al., 2020).

This model assumes that CO_2 forms a layer of constant effective thickness (h_{eff}) beneath the caprock once equilibrium is reached, long after the injection period. This simplification allows estimation of the maximum plume radius (r_{max}) using the following analytical relationship:

$$r_{max} = \sqrt{\frac{V_{tot}}{\phi \pi h_{eff}}}$$

where V_{tot} is the total injected CO_2 volume, ϕ the porosity of the storage formation, and h_{eff} the effective plume thicknesses.

b) MacMinn and Juanes Model (MacMinn and Juanes 2009).

This analytical model describes the post-injection migration of the CO_2 plume, governed by buoyancy and capillary trapping effects. The solution adopted in this study is an asymptotic solution describing plume spreading without considering capillary trapping, where the key parameters are the mobility ratio (M) and the capillary trapping number (Γ).

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The result is independent of the initial plume shape, depending solely on the total injected volume. The validity of the solution requires that the dimensionless time $(\pi \cdot \tau)^{1/4}$ be sufficiently large. It is also noted that an increase in the mobility parameter (M) delays the time required for the plume to reach this asymptotic regime.

3.2.2.2 Induced overpressures

The injection rate, coupled with site characteristics, produces a wide range of variation in pressure increases. We will use the approach of Mathias et al. (2009). This is an analytical model that depends on the viscosity and density of the fluids involved in the process. In this case, the presence of small compressibilities in the fluids and in the rock is also considered, instead of the radius of influence used in the other approaches. The analytical method developed by Mathias et al. (2009) was chosen instead of a semi-analytical method because, despite its higher accuracy, the complexity it introduces and the need for a larger amount of data make the analytical solution the best option at this stage of the risk analysis of the Lopín site.

The model assumes that capillary forces are negligible throughout the storage formation. The model assumes that CO_2 and brine are separated by a sharp interface located at a height 'h' from the base of the formation, and that if only one of the fluids is present, the saturation of that fluid is equal to unity (i.e., fully saturated in it).

This method also assumes that both relative permeability and viscosity are constant in each of the zones into which the reservoir is divided, and that the fluids and porous formation are slightly compressible. Finally, it does not consider density variations with depth within the reservoir rock and assumes that compressibility remains constant throughout the reservoir.

Multiple injection wells: The pressure calculation for multiple wells applied the principle of superposition, where the total pressure at any point is the sum of the pressure contributions from each individual well (Eq. (3)) (Joshi et al., 2016).

$$\Delta P(r_{well}, t)_{well\ 1} = \Delta P(r_{well}, t)_{well\ 1} + \Delta P(r_{well}, t)_{well\ 2} + \cdots \qquad (3)$$

3.2.3 Phase 1 results

This initial risk assessment phase focused on the *normal evolution scenario*, which models the expected system behaviour under stable storage conditions, accounting only for processes inherent to CO_2 injection.

The analysis was conducted using permeability and porosity datasets from WP2, with the selection restricted to reservoir intervals exhibiting porosities greater than 8%, thereby delineating the primary pathways for fluid flow. The selected data were statistically fitted to derive two distinct Probability Distribution Function (PDF) models for both porosity and permeability: a *Base Case* and a theoretical *Best (Optimum) Case*. Subsequent risk evaluations were performed employing both PDF configurations to encompass and constrain the uncertainty domain associated with these reservoir properties (see Figure 6).

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The assessment evaluated two distinct operational scenarios:

- **Pilot Scenario:** Limited to 100,000 tonnes of CO_2, with injection rates of 0.63 kg/s (to achieve the total volume over a 5-year research project) and 5.0 kg/s (to observe system behavior under more industrial-like flow rates within the same mass constraint).
- **Industrial Scenario:** Based on the site's preliminary estimated capacity of 13 Mt from WP2, considering injection rates of 11 kg/s (~50% of local annual emissions) and 20 kg/s (~100% of local annual emissions).

Table 4: Input parameters for the risk assessment cases.

Parameter	Pot_70 Base	Pot_70 Best	Pot_90 Base	Pot_90 Best
Formation Thickness (m)	70	70	90	90
Permeability, μ (m²)	$2.14 \cdot 10^{-15}$	$5.06 \cdot 10^{-15}$	$2.14 \cdot 10^{-15}$	$5.06 \cdot 10^{-15}$
Permeability, σ (m²)	$2.53 \cdot 10^{-15}$	$2.04 \cdot 10^{-15}$	$2.53 \cdot 10^{-15}$	$2.04 \cdot 10^{-15}$
Porosity, μ (%)	12.39	15.29	12.39	15.29
Porosity, σ (%)	2.97	3.02	2.97	3.02
Injection Rate - Pilot (kg/s)	0.63 and 5.0			
Injection Rate - Industrial (kg/s)	11 and 20			

3.2.3.1 Pilot case.

This case evaluates the injection of up to 100,000 tonnes of CO_2. The plume evolution and pressure buildup were calculated using the models described in Section 3.2.2 and the parameters from Section 3.2.1, considering various injection rates and aquifer thicknesses as summarized in Table 4.

For the Monte Carlo simulations, the plume evolution was calculated using the Nordbotten approximation for $\Gamma < 0.5$ and the Houseworth approximation for $\Gamma > 0.5$. Figure 10 illustrates the differences between these approximations, showing the results for the maximum plume extent and pressure increase at injection rates of 0.63 kg/s and 5.0 kg/s.

Plume Extent: The calculated probability density functions (PDFs) for both injection rates (see Figure 10) show that the probability of the CO_2 plume reaching the nearest existing faults or wells is negligible. For the 0.63 kg/s rate, the worst-case scenario (70m thickness, base case petrophysics) shows a less than 1% probability of the plume front exceeding 282 m. This distance decreases to 253 m for the 5.0 kg/s rate, as the plume shape is influenced by the Γ parameter.

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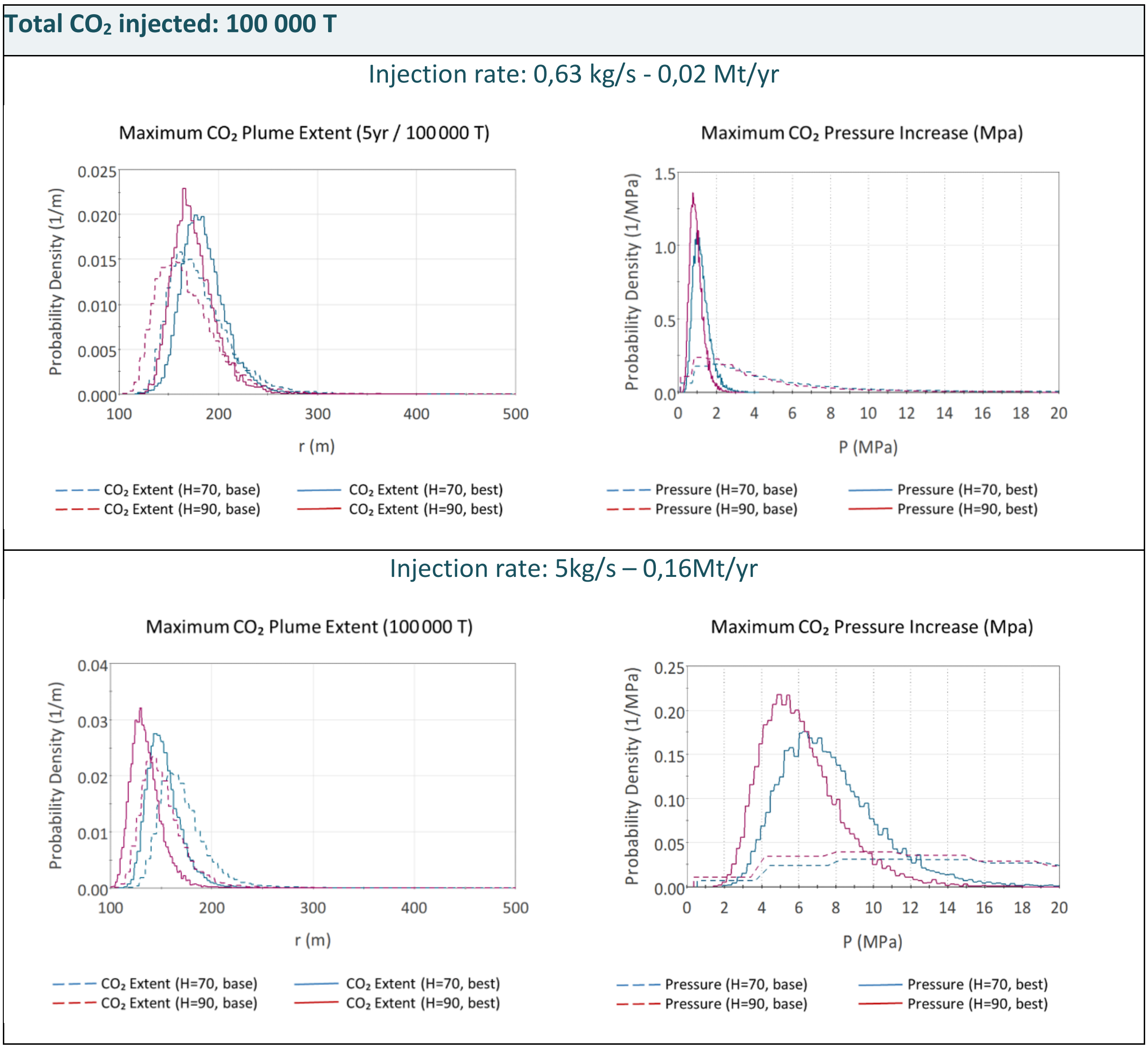

Figure 10: Maximum plume reach and maximum pressure increase shown for pilot case.

Pressure Buildup and Containment Risk: A leakage scenario through the seal would be triggered if the pressure buildup exceeds its mechanical strength. Prior to site-specific data on the seal's pressure limits, a conservative estimate was derived from the expression by Callas et al. (2022) (Eq. (4)):

$$\text{Fracture Pressure } (MPa) = 0.8 \cdot [23(MPa/km) \cdot (\text{Depth}(km) + \text{Thickness (h)}(km))] \quad (4)$$

A safe operating window was defined conservatively between 80% and 90% of this calculated fracture pressure. The resulting pressure limits for the Lopín Formation are shown in Table 5:

Table 5: Pressure buildup limits

Pressure Limit	Value (MPa)
Fracture Pressure	32.9
90% of Fracture Pressure	29.6
80% of Fracture Pressure	26.31

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The pressure increase corresponding to a 95% cumulative probability for all studied cases is summarized in Table 6. Cases exceeding the 80% fracture pressure limit are highlighted.

Table 6: Pressure increase for a 0.95 cumulative probability. Cases exceeding the 80% limit from Table 5 are in red.

Case	Pressure @ 0.63 kg/s (MPa)	Pressure @ 5.0 kg/s (MPa)
H*=70 base	13.53	78.43
H*=70 best	2.03	12.71
H*=90 base	10.70	63.00
H*=90 best	1.61	10.10

*Storage formation thickness (m)

In conclusion, the results confirm that the WP4 pilot scenario (0.63 kg/s) remains well within the established pressure thresholds, thereby ensuring full compliance with the requirements set forth in Directive 2009/31/EC. Conversely, increasing the injection rate to an industrial scale (5.0 kg/s) induces pressure buildups that surpass the conservative geological containment limits across all evaluated scenarios (values in red color in Table 6). These outcomes emphasize the critical influence of system uncertainties and their substantial implications for the assessment and management of potential risks.

3.2.3.2 Industrial case.

The industrial-scale scenario assesses the injection of 13 Mt of CO_2. This scale introduces greater uncertainties, primarily related to the ultimate extent of the CO_2 plume within the Buntsandstein B1 unit and the significant pressure buildup induced by the considered injection rates of 11 kg/s and 20 kg/s (see Table 4). These rates were selected to represent 50% and 100%, respectively, of the annual CO_2 emissions from nearby industrial plants.

Plume Extent: The results, shown in Figure 11, indicate that the maximum plume extent (for a 1% probability of exceedance) ranges from 2 027 m (20 kg/s, H=90, best case) to 2 848 m (11 kg/s, H=70, base case). The Nordbotten approximation was applicable across all scenarios, and the variation between the two injection rates was not significant in terms of final reach.

- **Abandoned Well (Lopín-1):** The probability of the CO_2 plume reaching the nearest abandoned well, located approximately 10 km from the injection point, is negligible in all cases.
- **Normal Faults:** In contrast, the models predict with a high degree of confidence that the CO_2 plume will interact with the nearest normal faults (400–600 m) during the industrial injection phase.

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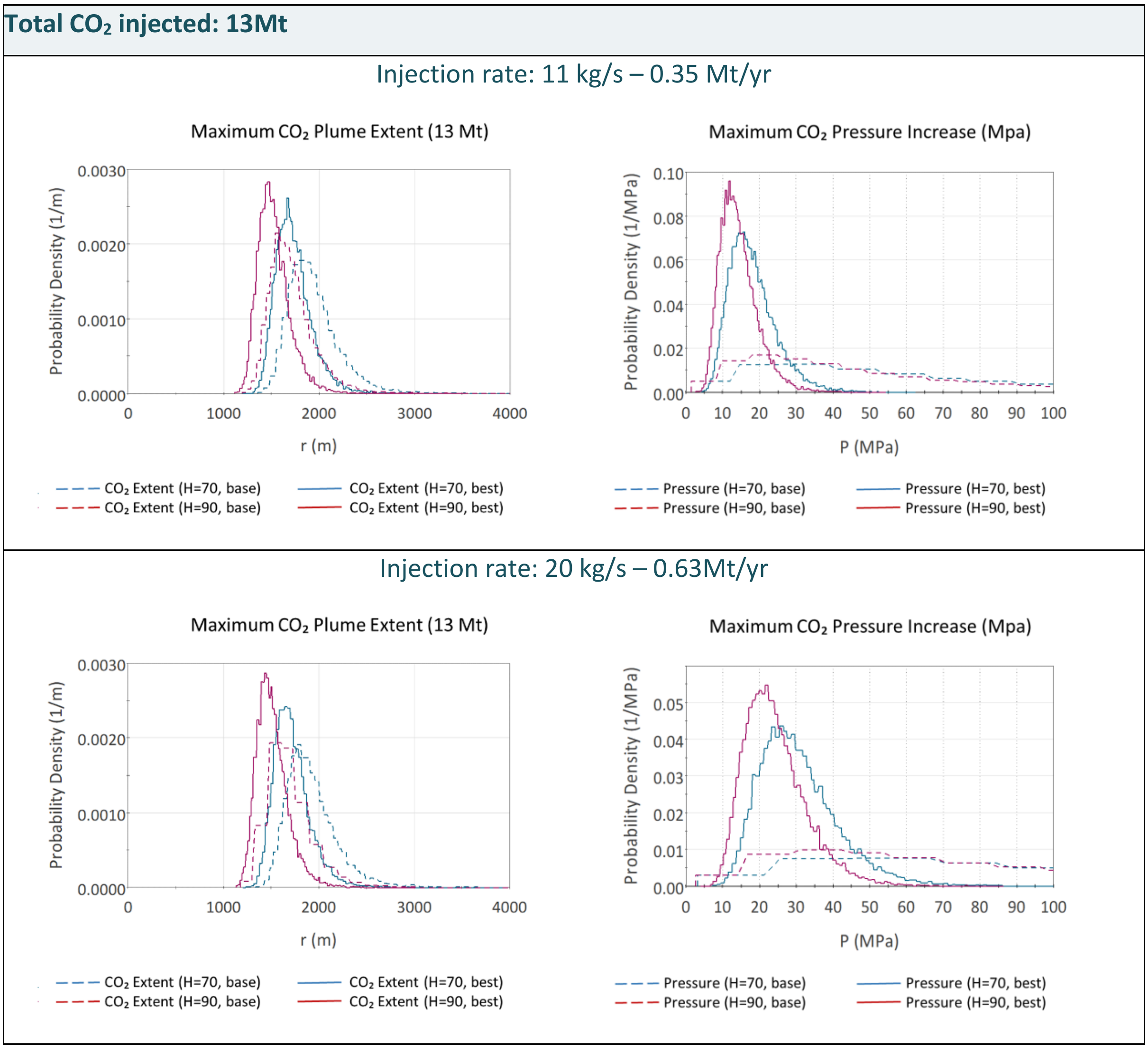

Figure 11: Maximum plume reach and maximum pressure increase shown for industrial case.

Pressure Buildup and Containment Risk: Table 7 presents the pressure increase corresponding to a 95% cumulative probability. The results demonstrate a high probability of exceeding the safe pressure limits defined in Table 5.

Table 7: Pressure increase for a 0.95 cumulative probability. Cases exceeding the fracture pressure limit from Table 5 are highlighted in red

Case	Pressure @ 11 kg/s (MPa)	Pressure @ 20 kg/s (MPa)
H=70 base	188.00	309.90
H=70 best	29.96	50.55
H=90 base	151.40	248.90
H=90 best	23.86	40.23

In conclusion, the pressure analysis reveals that the industrial-scale scenario entails a very high likelihood of exceeding the geological containment limits. The safe pressure thresholds are surpassed

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in all base-case and in most of the best-case scenarios. Only under the most favorable geological conditions (best-case parameters), combined with the lower injection rate (11 kg/s), does the resulting pressure buildup remain at or near the acceptable limit.

3.3 Preliminary risk evaluation. Pilot case.

The Monte Carlo simulation results for the pilot injection rate of 0.63 kg/s indicate a low-risk profile for the normal evolution scenario. The maximum CO_2 plume extent does not reach the bounding faults of the horst (located 400-600 m away) nor the nearest abandoned well (Lopín-1, ~10 km distant). Consequently, the CO_2 is expected to remain securely confined beneath the primary seal (B2 Formation).

Furthermore, the maximum induced pressures at the end of injection remain below 80% of the caprock's fracture pressure in all cases, indicating a very low probability of caprock failure or induced seismicity.

These results allow for a first estimation of the potential risk scenarios and the approaches to be adopted for their management in this initial phase of the study (Table 8)

Table 8: Preliminary scenarios risk assessment of the Pilot Case (defined by an injection rate of 0.63kg/s).

	SCENARIO	RISK EVALUATION
EVOLUTION SCENARIOS	**Leakage through wells** i. Leakage from an operating well ii. Leakage from an abandoned well	i. **2nd phase.** Pending the injection well design definition in WP4. ii. **No RISK (Modelization results).**
	Leakage through seal formation i. Through fracturing of the caprock due to over-pressurization ii. Due to sealing deficiency of the caprock	i. **No RISK (Modelization results).** ii. **No RISK (Regional seal-Keuper).**
	Leakage via existing faults	**No RISK (Modelization results).**
	Expected lateral extent exceeded (CO_2) i. Unexpected leak paths ii. Interaction with other resources	i. **No RISK (Modelization results).** ii. Not expected. Geothermal energy ruled out by temperatures
	Migration of formation brine outside expected boundaries. Interaction with other resources.	**No RISK.** Not expected. Geothermal energy ruled out by temperatures.
	CO_2 accumulation in a secondary reservoir following unexpected vertical migration	This scenario is **considered in the 2nd phase.** It will be linked to the leakage through faults/primary seal scenario as the possible secondary storage intersects a set of faults that pass through the secondary seal.

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PERTURBATIVE SCENARIOS	**Leakage as a result of seismic events**	**No RISK** No natural seismic event of any type is considered (area with one event 4 in its entire history). No induced seismicity activity (modelization results)
	Disruption by a later activity	**No RISK** No natural resources. Geothermal excluded by temperatures.
	Flow modifications	**Pilot injection: No RISK** No considered in the normal scenario. No/very low flow in the storage formation.
PERFORMANCE SCENARIOS	**Injectivity loss**	To be treated jointly with WP4 in **2nd phase.**
	Smaller capacity of the reservoir than expected	
	Reservoir pressurization due to unexpected compartmentalisation	
	Accidental over-filling	

Similarly, a preliminary risk assessment matrix summarizing these findings is presented in Table 9. The results confirm that the Lopín site is suitable for the safe pilot-scale storage of CO_2, complying with the requirements of Directive 2009/31/EC.

Table 9: Preliminary scenarios risk assessment matrix for the Pilot Case (0.63 kg/s injection rate).

Risk Scenario	Probability	Consequence	Risk Level	Justification
Leakage via bounding faults	Negligible	High	Very Low	Plume extent < 400 m to nearest fault.
Leakage via abandoned wells	Negligible	High	Very Low	Nearest well (Lopín-1) is ~10 km away.
Caprock failure / seismicity	Very Low	High	Low	Pressure buildup < 80% of fracture pressure.
Leakage through primary seal	Low*	Moderate	Low*	Secondary containment (Muschelkalk M1 & Keuper) exists.

*Assumes a hypothetical, undetected high-permeability zone.

3.3.1 Sensitivity Analysis and Recommendations for Phase 2

Despite the positive outlook for the pilot case, a sensitivity analysis (Figure 12) underscores that uncertainties in system parameters, particularly porosity and permeability, are critical and have significant implications for risk estimates, especially when considering industrial-scale injection.

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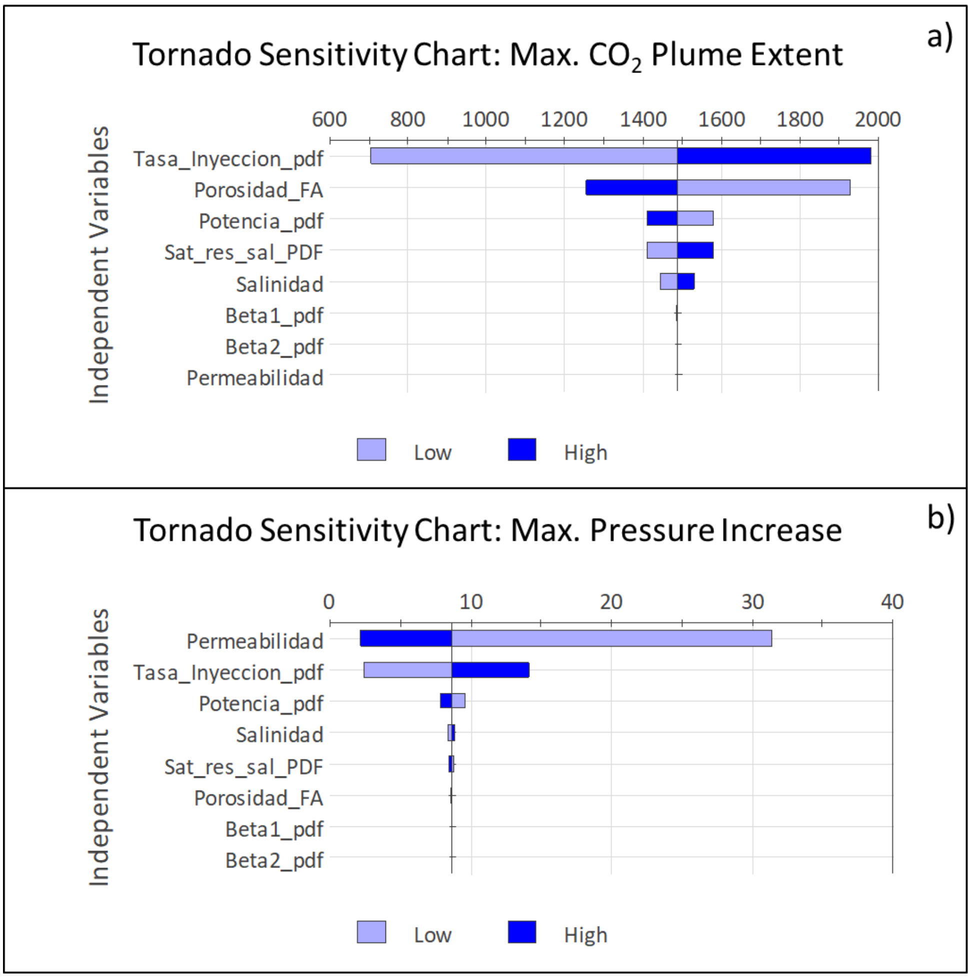

Figure 12: Tornado sensitivity charts showing (a) maximum CO_2 plume extent and (b) maximum pressure increase.

Based on the results of this phase, the following recommendations are proposed for Phase 2 of the risk analysis:

- **Refine Storage Formation Characterization:** Prioritize the reduction of uncertainty in porosity and permeability, as these are the dominant factors controlling pressure buildup, especially at higher injection rates.
- **Assess Caprock Integrity:** Conduct specific studies to verify the lateral continuity and geomechanical properties of the primary seal (B2 Formation). Although the probability of fracture is low, it cannot be entirely dismissed.
- **Enhance Geomechanical and Hydrogeological Characterization:**
    - **Hydrogeology:** Perform a detailed analysis of regional groundwater flow in the Buntsandstein and Muschelkalk formations to assess potential long-term interactions with the CO_2 plume, particularly post-injection.
    - **Geomechanics:** Incorporate site-specific geomechanical parameters to define the in-situ stress state of the basin and the behavior of system boundaries (faults).
- **Address Long-Term and Fault-Related Risks:**
    - **Normal Faults:** Characterize the sealing nature of the horst-bounding normal faults. Their current behavior (sealed, semi-permeable, or permeable) is a fundamental control on pressure dissipation and storage capacity.

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- **Reverse Faults:** Evaluate the probability of CO_2 leakage through deeper reverse faults that intersect the secondary regional seal (Keuper). While the initial probability is low, the potential consequences are significant.

In conclusion, while the pilot case demonstrates a strong safety case, optimizing the site characterization is essential to accurately define the admissible injection rates for industrial-scale scenarios, where the risk of exceeding safe pressure limits increases significantly.

3.4 Pilot Implementation Plan

The risk assessment results confirm that the pilot scenario complies with Directive 2009/31/EC. However, they also highlight the critical need to optimize site characterization to accurately define the maximum admissible injection rates, especially for industrial-scale operations where higher rates significantly increase the probability of exceeding safe pressure thresholds under unfavorable permeability conditions.

Pressure Limits and Probabilistic Analysis

The fracture gradient analysis provided a robust basis for defining the threshold pressures. At the reference depth (top perforations of the pilot injection well), 90% of the fracture pressure corresponds to 265 bar for the minimum value, 287 bar for the mean value, and 305 bar for the maximum value (Chassagne, 2023, D3.3). These values establish a conservative operational limit of 30.5 MPa for the pilot injection, as proposed by the Ebro Team under WP4. This upper limit was selected for Phase 1 calculations, assuming that subsequent characterisation would allow this value to be refined.

As injection rates increase, permeability becomes the key controlling factor for overpressure levels. Therefore, a probabilistic analysis was subsequently carried out to determine the injection rates that would ensure a ≤5% probability (95% cumulative probability) of exceeding this pressure limit. This assessment was performed for reservoir thicknesses of 70 m and 90 m, considering both the base-case and best-case porosity and permeability distributions.

Results for the Pilot Case

The maximum allowable injection rates for the pilot case are summarized in Figure 13. These rates represent the threshold at which the probability of exceeding the 30.5 MPa pressure limit is 5%.

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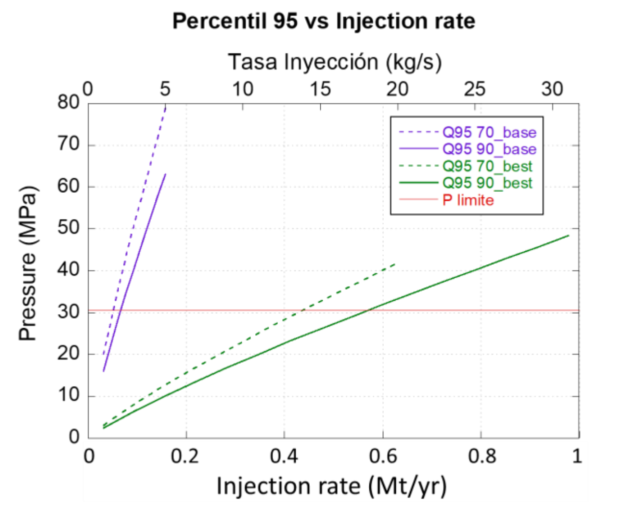
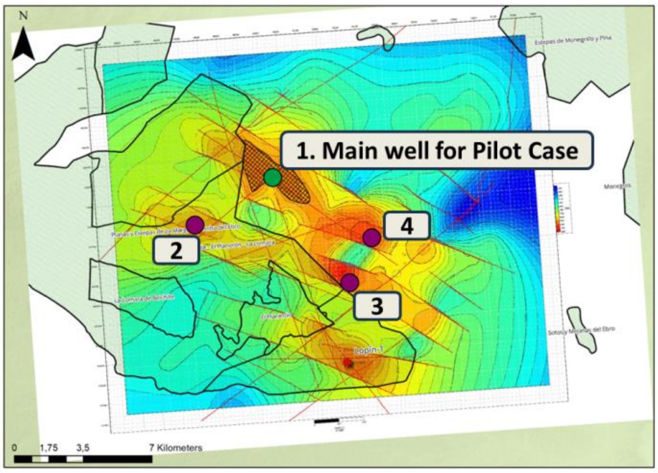


	Injection Rate	
Case	Mt/yr	Kg/s
H=70m; base	0.05	1.63
H=90m; base	0.07	2.15
H=70m; best	0.44	13.90
H=90m; best	0.62	19.68

Figure 13: Maximum allowable injection rates for the different pilot cases (5% probability of exceeding the 30.5 MPa limit)

Preliminary Analysis for an Industrial Case

An initial assessment for an industrial-scale scenario was performed, considering injection through one, two, or four wells, proposed cases in (Chassagne, R. 2024. D3.3) (see Figure 14 for well locations). The pressure calculation for multiple injection wells will apply the principle of superposition, as described in Section 3.2.2.2)



1.
X 0º 36´51,569" W
Y 41º 26´8,197" N

2.
X 0º 39´50,217" W
Y 41º 25´3,108" N

3.
X 0º 34´26,685" W
Y 41º 23´4,34" N

4.
X 0º 33´29,317" W
Y 41º 24´13,928" N

Figure 14: Ebro wells

The analysis focused on the best-case (most optimistic) petrophysical parameters to determine the upper performance limit of the system, without considering the maximum storage capacity of the formation. The results for maximum injection rates and total mass injected over 30 years are presented in Table 10.

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Table 10: Industrial-case results for best-case petrophysics.

Well	Max. Inj. Rate (Mt/yr)	Total CO_2 Injected in 30 yrs (Mt)
Well1	0.46	13.8
Well1 + Well2	0.39	23.7 (11.7/well)
Well1 + Well3	0.43	25.5 (12.8/well)
Well1 + Well4	0.41	24.7 (12.4/well)
All Four Wells	0.31	37.2 (9.3/well)

For context, under base-case petrophysical conditions, the maximum allowable injection rate for a single well (Well 1) was found to be only 59 kt/yr, resulting in a maximum of 1.78 Mt injected over 30 years. This starkly contrasts with the best-case scenario and underscores the dominant control of permeability on system performance.

4. Risk assessment synthesis

4.1 Risk Identification Update

The second phase of work involved collaborative sessions aimed at populating a comprehensive risk matrix template. This resulted in a refined list of safety scenarios for WP5. Key updates to the initial list in Section 3.1 are summarized in Table 11.

Table 11: Risk identification update.

	ORIGINAL	MODIFICATION/ADDITION
EVOLUTION SCENARIOS	Leakage through wells: ○ Leakage from an operating well ○ Leakage from an abandoned well	Split into two distinct scenarios. 1. Leakage from an operating well 2. Leakage from an abandoned well
	Exceeding expected lateral extent (CO_2): ○ Unexpected leak paths ○ Interaction with other resources	Split into two distinct scenarios: 1. Exceeding expected lateral extent (CO_2) 2. Structural spill. Both now include sub-item on: ○ conflicts with other land or subsurface uses.
	Migration of formation brine outside expected boundaries. Increased displacement of high salinity formation: ○ Interaction with other resources.	Sub-items updated to include: ○ conflicts with other land uses.

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		New scenario added: 1. Uplift or subsidence of ground
		New scenario added: 1. Unforeseen CO_2 impacts
PERTURBATIVE SCENARIOS:	Leakage due to seismic events (natural or induced). Induced seismicity can cause loss of mechanical integrity in the reservoir and other subsurface structures (especially in wells). ○ Fracturing, fault creation/reactivation ○ Loss of well containment	Split into two distinct scenarios: 1. **Natural seismicity.** Leakage due to seismic events (natural). Seismicity can cause loss of mechanical integrity in the reservoir and other subsurface structures (especially in wells). 2. **Induced seismicity**. Leakage due to seismic events (induced). Seismicity can cause loss of mechanical integrity in the reservoir and other subsurface structures (especially in wells). With the same subsections each.
PERFORMANCE SCENARIOS		New scenario added: 1. Unexpected variations in CO_2 composition

The initial screening of scenarios carried out during Phase 1 was updated, and the set of scenarios to be analysed in detail during Phase 2 was established (Table 12). For each scenario, the analysis addressed the plausible spatio-temporal leak patterns, the underlying failure mechanisms, and the associated environmental impacts. See Appendix 8.1 for a more detailed description of how each scenario is managed. See also Appendix 8.2, which contains a diagram showing the main causes and possible consequences of each scenario, as well as the proposed treatment of the threats.

Table 12: Phase 2. Consolidated Scenario Assessment Overview.

ID	SCENARIO	CATEGORY	ASSESSMENT APPROACH	KEY RATIONALE & FINDINGS
S1	Leakage from Operating Well	Evolution	Qualitative (WP4)	Very Low risk. Managed by standard well design, materials, and integrity monitoring.
S2	Leakage from Abandoned Well	Evolution	Quantitative	Negligible risk. Plume will not reach Lopín-1 well (~10 km away) per Monte Carlo simulations.
S3	Leakage through Seal Formation	Evolution	Semi-Quantitative	Low risk. Pressure increase below fracture limit; geochemistry shows self-sealing tendency; secondary regional seal present.

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S4	Leakage via Existing Faults	Evolution	Semi-Quantitative	Low/Very Low risk. Plume will reach normal faults, but subsequent migration is contained. No pathway to surface.
S5	Exceeded Lateral Extent (CO_2)	Evolution	Qualitative	Non-credible. Site structural closure and bounding faults ensure lateral containment.
S6	Structural Spill	Evolution	Qualitative	Non-credible. Prevented by conservative capacity estimates and active pressure management.
S7	Migration of Formation Brine	Evolution	Qualitative	Non-credible. Site is hydrogeologically isolated; no connectivity to freshwater resources.
S8	Uplift or Subsidence of Ground	Evolution	Qualitative	Negligible. Deep reservoir and plastic overburden absorb deformation.
S9	Unforeseen CO_2 Impacts	Evolution	Qualitative	Highly improbable. Systematic FEP analysis and site characteristics (remote, no receptors) mitigate this.
S10	Induced Seismicity	Perturbative	Semi-Quantitative	Moderate but manageable. Can be mitigated by pre-heating CO_2. Probability of exceeding fracture pressure calculated.
S11	Natural Seismicity	Perturbative	Qualitative (Dismissed)	Negligible threat. Very low local seismicity (Max M2.6). Regional events (M4.1) too distant.
S12	Disruption by Later Activity	Perturbative	Qualitative	Non-credible. No known economic geological resources at target depth.
S13	Flow Modifications	Perturbative	Qualitative	Non-credible for pilot. Small volume; deep aquifer has very slow/stagnant natural flow.
S14	Injectivity Loss	Performance	Qualitative (WP4)	Operational risk. Managed by well design and operational controls. Low safety impact.
S15	Smaller Capacity	Performance	Qualitative	Key uncertainty. Addressed via conservative estimates and phased injection for model calibration.
S16	Unexpected Compartmentalization	Performance	Qualitative	Key uncertainty. Managed via adaptive strategy; pilot injection will detect compartments.

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S17	Accidental Over-filling	Performance	Qualitative	Ruled out by design. MMV plan and pressure management will halt injection before limits.
S18	Variations in CO_2 Composition	Performance	Qualitative	Operational risk. Managed at capture facility; out of scope for geological assessment.

This initial selection process has made it possible to identify the most relevant scenarios for the Lopín site. These scenarios have been analysed in detail and, where possible, quantitatively, taking into account the available data and the results of our simplified probabilistic models and the detailed models of WP3. These are:

- Leakage through the seal formation.
- Leakage through abandoned wells.
- Leakage via existing faults.
- Induced seismicity.

Particular emphasis was placed on the most significant and uncertain aspects of Lopín, namely the influence of geochemical and geomechanical factors on risk scenarios.

4.1.1 Integration of Stakeholder Perception (WP6)

Input from WP6 (Deliverable D6.4) on stakeholder risk perceptions was incorporated into the Phase 2 analysis. Stakeholders collectively identified and ranked potential risks on a matrix based on their perceived importance and controllability (see Figure 15).

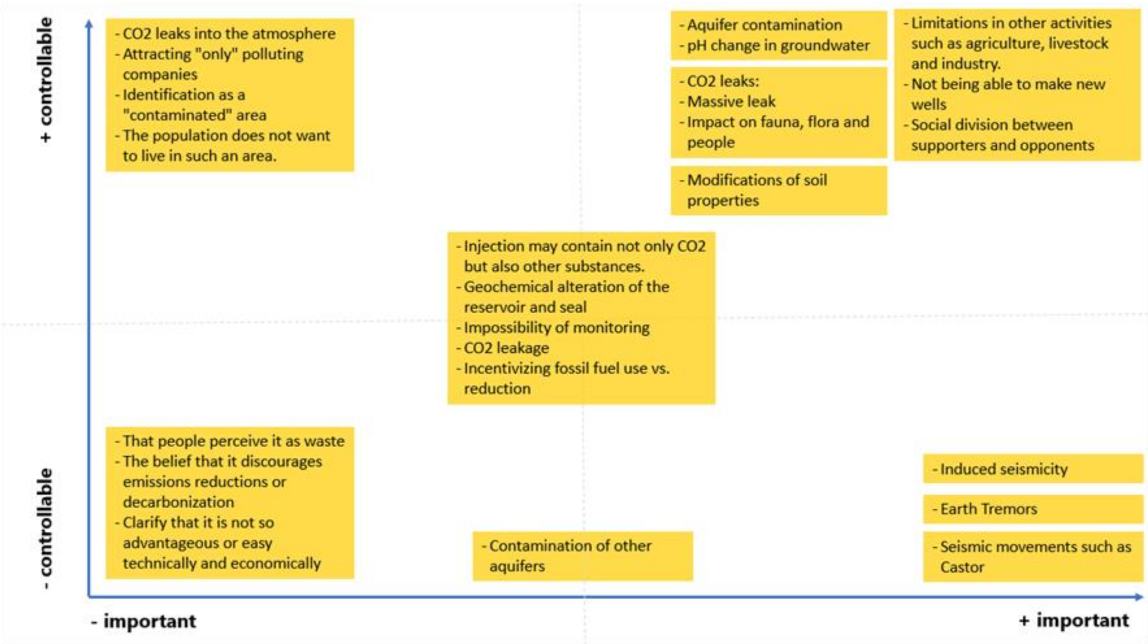

Figure 15: Stakeholder Risk matrix (Deliverable D6.4, 2023)

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A key finding was that all safety and environmental risks raised by stakeholders were already captured in the Phase 1 scenarios. However, the risk of seismic events was highlighted as highly significant and perceived as the least controllable. This feedback directly motivated the more detailed analysis of the Induced Seismicity Scenario. Given the very low natural seismicity of the Lopín area, the assessment focuses exclusively on injection-induced seismicity (Olaiz et al., 2024 D2.5).

4.1.2 Injection strategy as a Basis for Risk Analysis

The risk analysis for the aforementioned scenarios in Phase 2 will be based on the injection strategies defined in WP4 (Canteli et al., 2025. D4.3), as outlined in Table 13. These strategies will be analyzed for both the injection (30 years for industrial cases) and post-injection (up to 1000 years) phases. In the case of injection through two wells, the distance between the wells is 4.6 km (Deliverable 3.4 - draft version). Given this distance, the probability of interaction between the CO_2 plumes is negligible. However, this is not the case for the interaction between the pressure fronts, the spatial disturbance range of which extends to significantly greater distances.

Table 13: Injection strategies, as defined within WP4

Cases: Estimated capacity	Pilot	2.1 Mt	4.2 Mt	23 Mt
Injector wells (n)	1	1	2	1 or 2
Injection rate per well (Mt/yr / kg/s)	0.03 /0.95	0.07 / 2.22	0.07 / 2.22	0.5 / 15.85
Storage Years	3	30	30	Until max capacity

As per Deliverable D4.9 (Canteli *et al.,* 2025b), several injection options are considered due to existing uncertainties. The exploration phase includes an initial test injection of 0.03 Mt/yr for 3 years.

- **Conservative Case (0.07 Mt/yr):** This scenario is based on the base-case geology (WP2, Wilkinson, M. 2023, D2.7). The injection rate is calculated to not exceed the system's pressure limit (305 bar), resulting in a maximum storage capacity over 30 years.
- **Optimal Case (0.5 Mt/yr):** This scenario assumes a system with best-case petrophysical properties (porosity & permeability). Here, the maximum injection rate without exceeding the pressure limit is ~0.5 Mt/yr, considered for 1 or 2 wells (Table 8).

Additionally, the analysis will consider the limiting injection parameters from WP3 (Deliverable D3.4, 2025), which incorporate updated permeability/porosity data (see section 4.2.1) and a refined geological model. The corresponding capacities and rates are shown in Table 14.

In all the geological models that have been considered, it is assumed that faults act as hydraulic barriers, compartmentalising the system, only where they do not connect permeable units (Canteli *et al.,* 2025b, D4.3; Deliverable D3.4, 2025).

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Table 14: Optimal injection rate using a max BHP of 285 bar (adapted from WP3, Deliverable D3.4).

Cases: Estimated capacity (Mt)	6.12	7.62	8.45	11.17	14.90	15.51
Injector wells (n)	1	1	1	2	2	2
Injection rate per well (Mt/yr)	0.204	0.254	0.282	0.186	0.248	0.258
Storage years	30	30	30	30	30	30

4.2 Risk Analysis

This section presents the risk analysis results for the most relevant scenarios at the Lopín site, covering both pilot-scale and industrial-scale injection cases.

The assessments are based on Monte Carlo simulations that provide probabilistic values for CO_2 plume extent and induced overpressure in the reservoir. These simulations considered various parameter sets (Section 4.2.1) and injection rates (Table 13 and Table 14), yielding results for both the injection phase and the subsequent 1000-year post-injection phase. Results are presented for two distinct stages:

- Injection phase
- Post-injection phase (1000 years)

These analyses identify critical factors affecting long-term storage security and highlight key uncertainties requiring further detailed evaluation.

The injection rate, combined with reservoir geological properties (primarily permeability and porosity), generates significant variability in pressure buildup and plume extent. These variations substantially influence the applicable risk scenarios for the site. Therefore:

- Section 4.2.1 describes all porosity and permeability datasets used, including probability distributions (PDFs) associated with new experimental values obtained during Phase 2 of the project.
- Section 4.2.2 presents probabilistic results for plume extent limits and pressure increases, which will serve as reference for subsequent risk scenario analyses.

Another crucial aspect of risk analysis is the site's geochemical behavior following supercritical CO_2 injection. A synthesis of this geochemical analysis is presented in Section 4.2.2.1, as its conclusions are essential for understanding the system's chemical evolution and potential implications for storage integrity.

Sections 4.2.3 to 4.2.6 include analyses of the following scenarios:

- Leakage through wells (via operational/active or abandoned wells).
- Leakage through seal formation (due to caprock fracturing by over-pressurization or sealing deficiency).
- Leakage via existing faults.

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- Induced seismicity scenario.

These scenario analyses will build upon the results from the aforementioned modeling efforts.

4.2.1 Data Update

This section details the updates to the risk analysis stemming from improvements in the site characterization from WP2, specifically the integration of new data from the **CHIPRANA-1 well** (81 samples from the B1 Formation).

The probabilistic analysis incorporated three distinct cases for porosity and permeability, representing different levels of knowledge and data quality (See Table 15 and Figure 16)

Table 15: Petrophysical Parameter Distributions for Risk Analysis: New Data Case.

Parameter & Case	Distribution Type	Parameters (Mean, μ; Std. Dev., σ)	95% Confidence Interval for Parameters
POROSITY (%). New Data Case	Normal	μ = 12.97, σ = 2.59	μ: [12.29, 13.45]; σ: [2.17, 2.89]
PERMEABILITY (mD) New Data Case	Log-Normal*	μ = 3.38, σ = 1.72**	μ: [2.91, 3.80]; σ: [1.47, 2.26]

**Note: Parameters are for the log-normal distribution of the permeability values.*
***The standard deviation (σ=1.72) is for the underlying normal distribution of the log-values.*

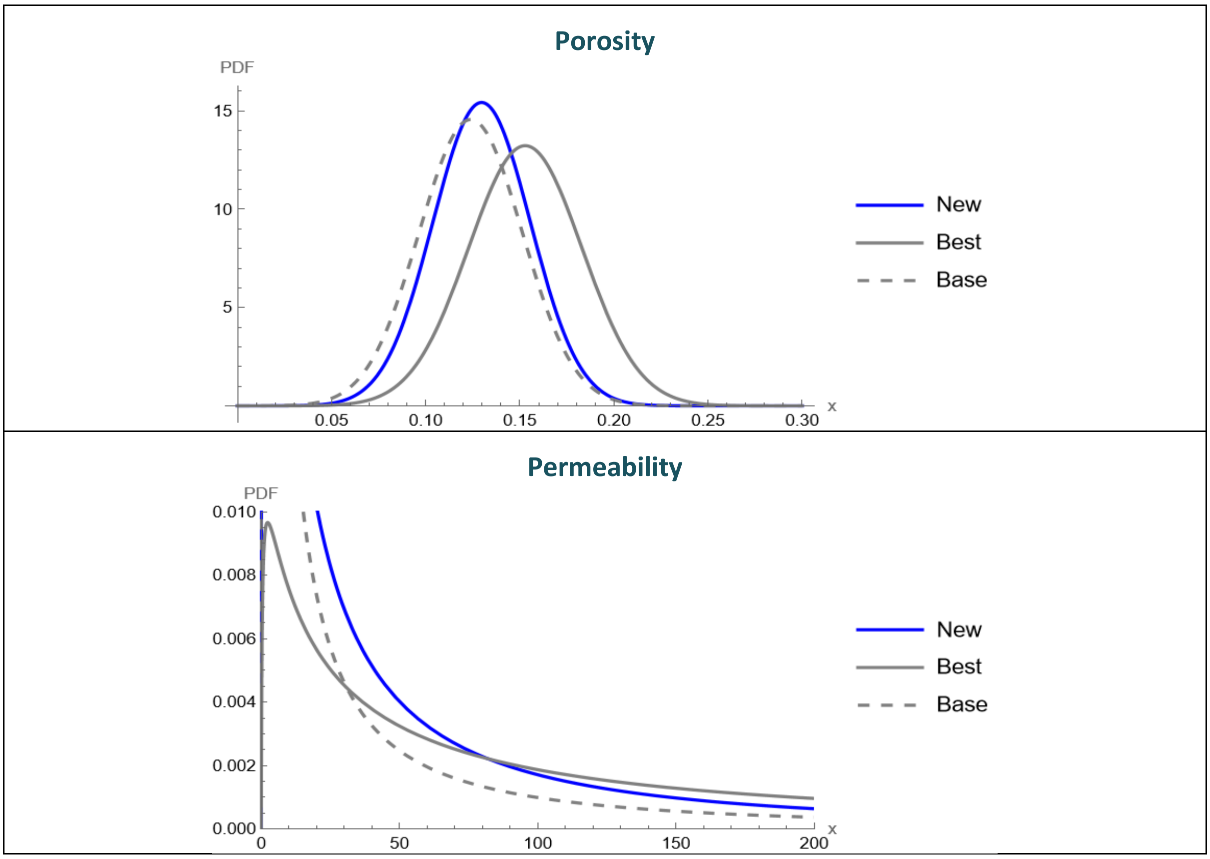

Figure 16: Graphical representation of the Petrophysical Parameter Distributions for the Risk Analysis Cases: Base, Best and New.

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The rationale for each case is as follows:

- **Base Case (Initial Characterization):** This scenario used all initially available data to derive the first set of Probability Distribution Functions (PDFs). It represents the conservative starting point, capturing the significant uncertainty from limited or sparse data.
- **Best Possible Case (Theoretical Optimum):** This scenario represents an idealized endpoint where data limitations are absent. Synthetic data were generated from the same statistical population as the base case, simulating the effect of infinite, error-free sampling. The resulting PDFs provide a theoretical upper bound on the precision of our estimates.
- **New Data Case (Improved Characterization):** This scenario incorporates the additional, real-world measurements from the **CHIPRANA-1 well**. As expected, the refined PDFs for this case show a reduction in uncertainty compared to the Base Case, but do not reach the theoretical optimum of the Best Case. This represents the most current and realistic assessment, reflecting the iterative nature of site characterization.

4.2.2 Modelling and Simulation Results

In Phase 2, the simulations relating to the extension of the CO_2 plume and the overpressures generated by injection were updated. Additional modelling efforts were conducted to assess other processes potentially affecting the integrity and safety of the storage system. These included the geochemical and geomechanical evolution of the reservoir and the development of the thermal front resulting from CO_2 injection at a temperature lower than that of the formation. As the propagation of this thermal front and its potential impact on normal faults could influence the system's geomechanical behaviour, a probabilistic assessment of its possible extent was conducted.

4.2.2.1 Geochemical aspects for CO_2 Storage in Lopín

This geochemical assessment evaluates the long-term integrity of the Lopín storage complex (Buntsandstein B1 reservoir and B2 seal) following CO_2 injection. The geochemical environment of the deep Buntsandstein aquifer in Lopín is mainly governed by the CO_2–H_2O and SiO_2–CO_2–H_2O systems. The aquifer is characterized by a predominantly siliciclastic lithology, composed mainly of quartz and feldspars, with ferrous oxides coating the mineral grains.

For this case, where dissolution–precipitation and possibly redox reactions are expected, the PHREEQC code (USGS) in combination with the EQ3/6 thermodynamic database (Lawrence Livermore National Laboratory) provides a reliable and efficient framework for geochemical modelling. This configuration allows for the quantitative evaluation of aqueous speciation, mineral equilibria, and gas–water–rock interactions under reservoir conditions.

The PHREEQC-based simulations enable the assessment of water chemistry evolution and mineral phase stability following CO_2 injection, offering insights into the main geochemical trapping mechanisms and the long-term behavior of the storage system. The geological model and initial mineralogical data are derived from the site characterization work in WP2 (Moreno et al., 2023, D2.7 EBRO BASIN SPAIN. ANNEXES).

Methodology

- **Approach**: Batch reaction modeling in two stages: (1) pre-injection equilibrium, and (2) perturbation by massive CO_2 injection (pCO_2 = 143.5 bar, T = 49°C) using PHREEQC Interactive (Parkhurst & Appelo, 1999).

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- **Mineralogy Input** (Moreno et al., 2023, D2.7 EBRO BASIN SPAIN. ANNEXES):
    - **Reservoir (B1):** Quartz (98%), K-feldspar (1%), Goethite (1%)
    - **Seal (B2):** Quartz (34%), Mica (18%), Ca-Montmorillonite (15%), Calcite (13%), K-feldspar (10%), Chlorite (10%) (see Figure 17)
- **Model Scenarios**: For the seal, we modeled a range of CO_2 migration scenarios (25%-100% of reservoir pressure).
- **Important Note**: The model used meteoric recharge water as initial condition to isolate CO_2-rock interaction processes, acknowledging the actual formation contains native brine (~190,900 ppm NaCl in Monegrillo-1 well) (Wilkinson, M. 2023, D2.7).

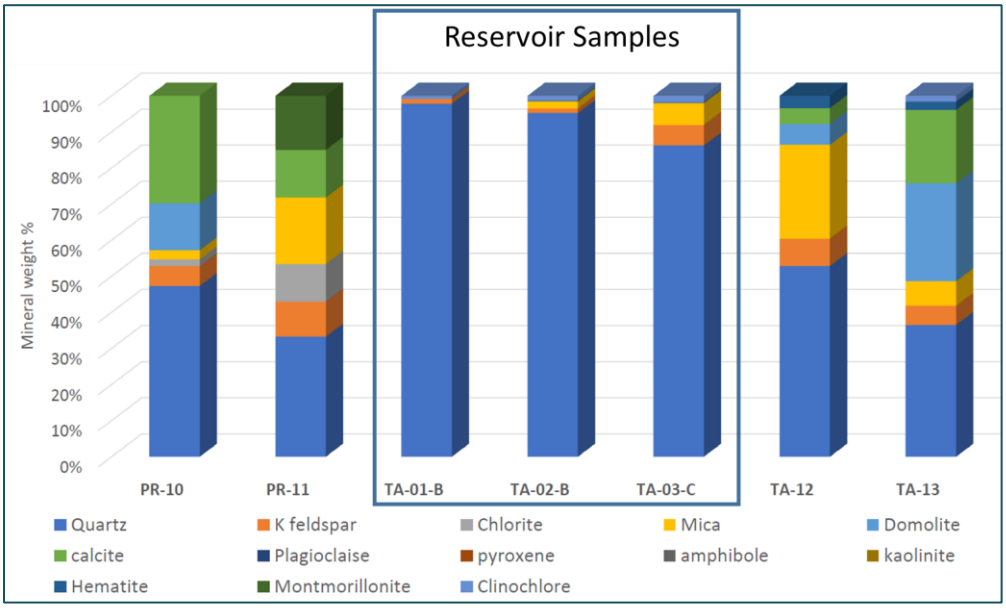

Figure 17: XRD analysis of Buntsandstein outcrop samples at Torre de las Arcas. Personal communication [from Manuel Ron, May 29, 2025.]

Key Findings and Risk Assessment

a. Reservoir Unit (Buntsandstein B1)

- Acidification Impact: CO_2 injection causes significant acidification (pH drops to ~3.4), promoting dissolution of K-feldspar (Saturation Index, SI = -5.75).
- Self-limiting Process: The released ions (K^+, Al^{3+}) and SiO_2 drive precipitation of secondary minerals like Kaolinite (SI = 7.77), creating a self-regulating system.
- Net Effect: While some local porosity increase may occur, the low initial feldspar content (<2%) and concurrent precipitation limit significant permeability changes at formation scale (see Table 16)
- Risk Level: LOW - Geochemical alterations are not expected to compromise reservoir integrity.

b. Seal Unit (Buntsandstein B2)

- Critical Minerals Stability: Even under worst-case CO_2 exposure, the key sealing minerals (Ca-Montmorillonite, Mica, Chlorite) remain in equilibrium (SI ≈ 0).

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- Dominant Precipitation Trend: Strong and consistent oversaturation of Kaolinite (SI = 2.39-2.57), Dolomite (SI = 2.46-2.89), and Goethite across all scenarios indicates a tendency toward pore clogging.
- Net Effect: The geochemical response suggests a reduction in porosity and permeability through "self-sealing" mechanisms (see Table 17).
- Risk Level: VERY LOW - The seal shows chemical resilience and potential improvement of barrier function.

Table 16: Modifications of key parameters in the solution before and after CO_2 injection in B1.

Parameter	Solution before CO_2 injection	Solution after CO_2 injection and equilibration with the aquifer mineralogy	Interpretation
pH	6.059	4.322	−28.7 %
Conductivity (µS/cm, 69 °C)	63	2244	+3462 %
Al total (mol/kg)	2.805e−04	5.544e−03	+1,876 %
K^+ (mol/kg)	2.805e−04	5.496e−03	+1,859 %
Si as H_4SiO_4 (mol/kg)	4.118e−04	3.953e−04	No changes / slight decrease within uncertainty range (−4.01 %)
HCO_3^- (mol/kg)	6.384e−05	1.433e−02	+22,347 %
SI Gibbsite	2.91	3.40	Slight increase
SI Kaolinite	6.78	7.77	Slight increase
SI K-mica	12.15	13.15	Slight increase

Table 17: Summary of Caprock (B2) Response to CO_2 Exposure

Parameter	100% pCO_2	75% pCO_2	50% pCO_2	25% pCO_2	Trend
Specific Conductance (µS/cm)	50,585	46,015	38,926	27,296	Decreasing
pH	5.83	5.84	5.87	5.92	Slight increase
Key Mineral SI					
Ca-Montmorillonite	0.24	0.24	0.25	0.25	Stable
Kaolinite	2.57	2.56	2.55	2.52	Precipitation
K-feldspar	-7.64	-7.63	-7.61	-7.58	Dissolution

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Implications for Storage Safety

a. Overall Risk Evaluation

The modeling predicts a favorable geochemical evolution for long-term storage security. The system demonstrates natural self-regulation in the reservoir and self-sealing tendencies in the caprock. Geochemical alterations do not represent a significant containment risk.

b. Recommendations for following Phases

- Model Validation: Conduct flow-through experiments with representative rock samples to validate predicted dissolution/precipitation rates.
- Brine Chemistry Modeling: Perform complementary simulations using the native brine salinity (~190,000 ppm NaCl) as initial condition to assess its impact on geochemical evolution and well materials corrosion risk.
- Monitoring Strategy: Include K^+ and HCO_3^- tracking in the fluid monitoring program as key indicators of feldspar dissolution.
- Advanced Modeling: Implement reactive transport modeling to quantify spatial and temporal evolution of permeability changes.

Conclusion

The Lopín storage complex demonstrates robust geochemical characteristics suitable for CO_2 storage. The reservoir's quartz-dominated composition provides inherent stability, while the clay-rich seal shows favorable self-sealing behavior when exposed to CO_2. Geochemical reactions pose low risk to long-term containment integrity, supporting the site's viability for safe CO_2 storage operations. A key recommendation for next Phases is to confirm these findings by modeling the system with native brine conditions (Wilkinson, M. 2023, D2.7) to assess potential impacts on geochemical evolution and well integrity.

4.2.2.2 CO_2 Plume extent and Pressure increase

To assess the spatio-temporal patterns of potential CO_2 leakage and the underlying failure mechanisms, Monte Carlo simulations were applied. These models were used to determine the probabilities of two key events: a) the CO_2 plume reaching risk elements such as faults or existing wells, and b) the pressure buildup exceeding the fracture limits of the primary seal formation (Chassagne, 2024, D3.3). This analysis builds upon the models described in Section 3.2.2 which were applied to the injection strategies defined in WP3 and WP4 (Table 13 and Table 14).

Furthermore, it should be noted that, based on the detailed geochemical simulations presented in Section 4.2.2.1, no appreciable long-term reductions in reservoir porosity or permeability are expected due to mineral precipitation. The geochemical system is self-limiting, and the minor porosity changes resulting from secondary mineral growth (e.g., Kaolinite) are not forecasted to significantly alter the large-scale hydraulic properties of the storage formation. This finding supports the use of constant petrophysical properties in the dynamic plume and pressure models.

Probabilistic Framework and Methodology

The probabilistic simulations, based on the scenarios defined in Deliverable 3.4, explore the coherence between the detailed modeling from WP3 and the probabilistic approach developed in WP5. Key characteristics of this WP5 methodology are:

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- The use of discrete P10, P50, and P90 scenarios from WP3 is not required, as the variability in porosity and permeability is inherently accounted for through Probability Density Functions (PDFs) derived directly from experimental data.
- Two reservoir thickness configurations were included, as Phase 1 sensitivity analyses revealed this parameter significantly influences both pressure evolution and plume migration.
- The results presented in the following figures show the plume extent or pressure increase values that have only a 5% probability of being exceeded (i.e., the 95% cumulative probability limit). This provides a conservative, safety-focused estimate for decision-making.

Results: Plume Extension and Pressure Buildup

The probability functions obtained for plume extent and pressure increase have established the values corresponding to a 95% cumulative probability of not being exceeded. These values, representing the CO_2 plume extent during the injection phase and after 1000 years of post-injection, as well as the maximum pressure increase for one or two wells, are shown below (Figure 18 and Figure 19).

- **Plume Extent** (Figure 18): The figure illustrates the maximum extent of the CO_2 plume during the injection phase and the subsequent post-injection period. It also shows the distance to the nearest fault, located approximately 400 metres from Injection Well 1. The distance to the Lopín-1 well, situated around 10 km away, is not displayed, as it lies far beyond the probabilistic plume extents obtained in all cases. As can be seen, in all scenarios except the pilot case at the end of the injection period, the CO_2 plume front is expected to reach the nearest fault. These results underscore the importance of examining the fault-leakage scenario in detail, which is addressed in in Section 4.2.4. It should be noted that the post-injection (1000-year) results are based on an analytical approximation that considers only the injected volume and disregards both the plume geometry at the end of the injection period and capillary trapping. This explains the similarity of the solutions across all cases.
- **Pressure Buildup** (Figure 19): The figures display the maximum pressure increase reached during the injection phase, along with the maximum (30.5 MPa) and average (28.5 MPa) pressure limits used in Phase 1 and Phase 2, respectively. The injection rate range extends up to 0.5 Mt/yr, which represents the upper limit established by WP4 for the industrial-scale injection scenario based on Phase 1 results (Section 3.4). The results indicate that, for the “Base-case” permeability and porosity, overpressure values exceed the limits in all cases except the pilot case. For the “New-case” and “Best-case” porosity/permeability cases, the safety margin associated with the injection rates increases, consistently being more favourable for a single well than for two wells. These results highlight the necessity of detailed assessment of leakage through the seal and induced seismicity, covered in Sections 4.2.5 and 4.2.6.

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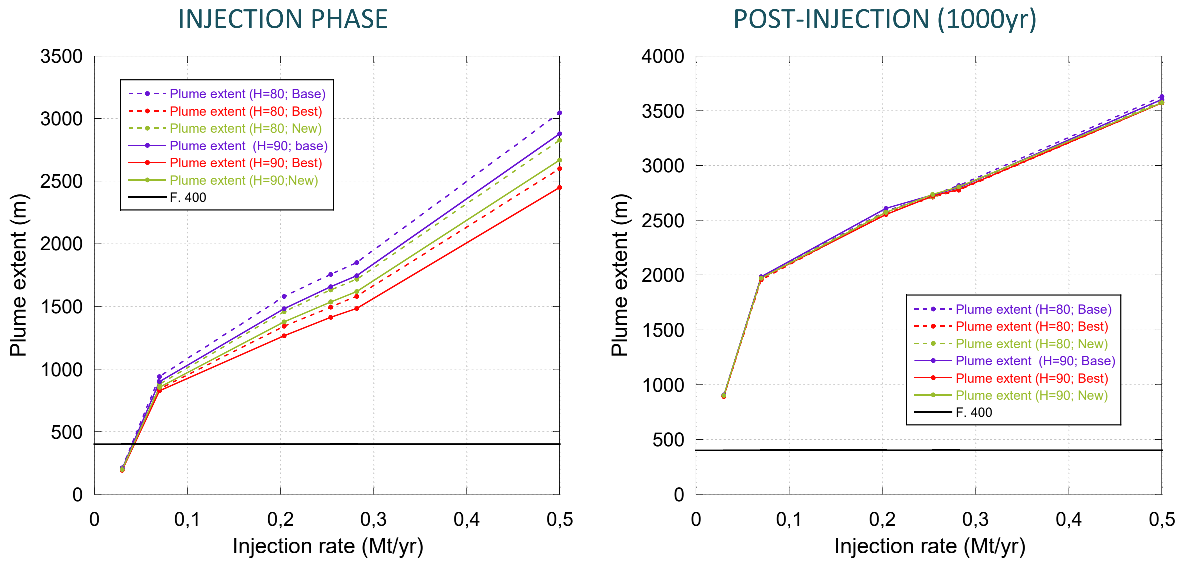

Figure 18: 95% cumulative probability limit for maximum CO_2 plume extent for the different injection rates defined in the injection strategies. The 400m distance, marking the approximate location of the nearest fault, is shown for reference. 'Base', 'Best', and 'New' refer to the porosity and permeability values used in the simulations for each case. 'H' refers to Storage formation thickness (m).

Discussion and Comparison with WP3 Results

The comparison between the deterministic (WP3) and probabilistic (WP5) results confirms a strong overall agreement in both the predicted pressure increase and the CO_2 plume migration behavior (see the appendix 8.3.1 for further details).

The probabilistic results for the CO_2 plume extent during the injection phase, obtained with analytical models, show very good agreement with the detailed numerical simulations from WP3. It is important to note that for long-term simulations, the probabilistic approach can be considered conservative. It does not incorporate several trapping mechanisms represented in the detailed WP3 models—such as capillary trapping and CO_2 dissolution into the formation water—which tend to reduce the plume's effective extent over time. Consequently, the probabilistic results likely overestimate the long-term CO_2 plume migration, ensuring a safety-biased representation of the long-term storage behavior.

4.2.2.3 Geomechanical aspects

The geomechanical assessment of the Lopín storage site was based on the Mohr–Coulomb failure criterion, which relates shear stress to the effective normal stress and the friction coefficient acting on potential fracture planes. The analysis considered both stress perturbations induced by CO_2 injection (overpressure) and those associated with thermal contraction due to the injection of CO_2 at a lower temperature than the formation. The geomechanical development of this scenario has been based on the methodologies presented in Rutqvist 2011, 2012 and Vilarrasa 2019.

Using in-situ stress data derived from nearby wells (Ebro-1, Ebro-2, Mayals, and Lopín) and calibrated through 1D geomechanical modelling performed with software GEOSmart™ (© Petrabytes Corp. and Repsol), the **principal stresses at reservoir depth** (approximately 1,760 m) were estimated as:

- S_{hmin} = 30.67 MPa - 33.45MPa
- S_{Hmax} = 40.72MPa - 44.42 MPa

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- S_v = 42.24 MPa
  Laboratory data provided an unconfined compressive strength (UCS) of 83.6 MPa, consistent with regional correlations.

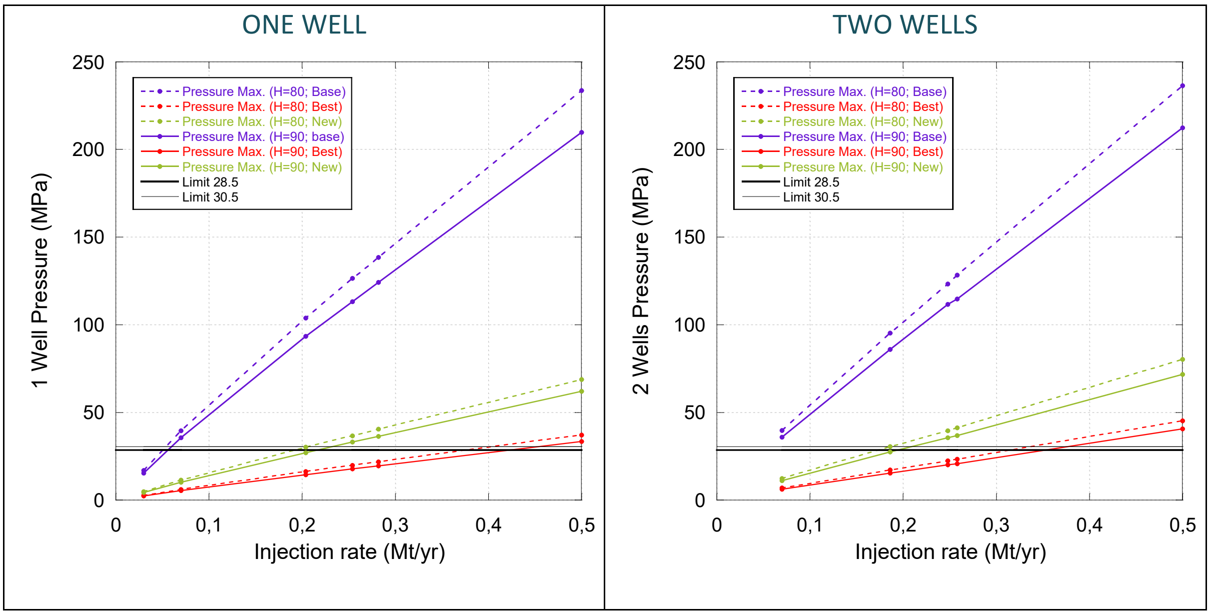

Figure 19: 95% cumulative probability limit for the maximum pressure increase due to CO_2 injection for the different injection rates. The system's pressure limits of 30.5 MPa and 28.5 MPa are shown for reference. . 'Base', 'Best', and 'New' refer to the porosity and permeability values used in the simulations for each case. 'H' refers to Storage formation thickness (m).

System considerations:

- A conservative friction angle (ϕ = 30°, μ = 0.58) was assumed to evaluate the potential for shear reactivation.
- The average pre-injection pore pressure (P_i) at a depth of 1,760 m is estimated to be 21.5 MPa, considering the overpressured conditions of the storage interval.
- The maximum allowable pressure is specified as 30.5 MPa and is directly constrained by the fracture pressure (Chassagne 2024, D3.3).
- Assuming a single injection well and a maximum injection rate of 0.18 Mt/year, with a reservoir thickness of 70 m, the overpressure (ΔP) required to reach but not exceed the maximum allowable pressure at the 95th percentile is 14.35 MPa.
- Stability condition of a fault: Coulomb's simple criterion. The fault will be stable as long as the shear stress is less than the shear strength.
- Shear reactivation probability: stress along the fracture plane greater than the critical shear stress for slip
- Shear reactivation probability: stress along the fracture plane greater than the critical shear stress for slip

Results

- Shear strength margin before injection σ'_{mci}.

$$\sigma'_{mci} = 3\sigma'_h - \sigma'_H$$

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$$with\ \sigma'_h = S_h - P_i \quad and \quad \sigma'_H = S_H - P_i$$

σ'_h = 30.67- 21.5= 9.17 MPa
σ'_H = 40.72- 21.5 = 19.22 MPa
σ'_{mci} = $3\sigma'_h - \sigma'_H$ = **8.29 MPa**

- Tensile strength margin σ'_{mc}

$$\sigma'_{mc} = \sigma'_{Hc} - \sigma'_H$$

$\sigma'_{mc} = 3(S_h + \Delta\sigma_h - P_i - \Delta P) - (S_H + \Delta\sigma_h - P_i - \Delta P) = \sigma'_{mci} + 2(\Delta\sigma_h - \Delta P) = \sigma'_{mci} + 2(\Delta\sigma_h - \Delta P) =$ 8.26+ 2(10.76 – 14.35) = **1.08 MPa**

The results indicate that the computed shear stress remains below the critical shear strength for optimally oriented fractures. Consequently, fault reactivation and induced seismicity are not expected under the planned injection conditions.

Although uncertainties in estimating the in-situ stress field are relatively small, particularly for the maximum horizontal stress, S_{Hmax}, the tensile strength margin is low. Therefore, the inclusion of thermal effects is essential for a proper assessment of the potential for fault reactivation.

Effect of Cooling on Fracture Stability

Temperature drop reduces tensile strength near the injection well. The change in thermal stress induced by the cooling of the rock around the injection well can be estimated by:

$$\sigma'_{mc} = \sigma'_{mci} + 2(\Delta\sigma_h + \Delta\sigma_T - \Delta P);$$

$$\Delta\sigma_T = \alpha_T \times \Delta T \times E / (1 - 2\nu)$$

with $\alpha_T = 1 \times 10^{-5}$ °C^{-1}, linear thermal expansion coefficient; E = 6 GPa, Young's modulus; and ν = 0.2, Poisson's ratio.

The results, as a function of the temperature difference between the injection fluid and the reservoir formation, are as follows:

ΔT=20°C $\Rightarrow$ **$\sigma'_{mci} + 2(\Delta\sigma_h - \Delta P + \Delta\sigma_T)$ = 8.26 + 2(10.76 – 14.35 – 2.0) = -2.92 MPa**

ΔT=10°C $\Rightarrow$ **$\sigma'_{mci} + 2(\Delta\sigma_h - \Delta P + \Delta\sigma_T)$ = 8.26 + 2(10.76 – 14.35 – 1.0) = -0.92.**

A negative value of σ'_{mc} near the well indicates that the calculated shear stress exceeds the fracture shear strength, implying that slip and induced seismicity could potentially occur in the near-well zone under cooling conditions. Therefore, it is necessary to determine whether the cold front can reach the faults (section 4.2.2.4).

4.2.2.4 Temperature Front

The temperature difference between the injected CO_2 and the storage formation generates a thermal front that can affect the reservoir's mechanical stability. This front advances through an advective-diffusive process during injection, becoming predominantly diffusive post-injection.

To model this phenomenon, two analytical approximations were used to bracket the potential behavior:

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a) Chesnokov et al. (2024) Model: This axisymmetric 1D model provides a more realistic representation by accounting for Joule-Thomson (J-T) cooling and quasi-steady-state heat exchange with adjacent layers, leading to a faster dissipation of the induced cooling.

b) Mathias et al. (2010) Model: This alternative approach assumes an adiabatic reservoir, ignoring heat exchange with the surrounding formations. This simplification offers a more conservative approximation, predicting more pronounced local cooling as it does not consider the thermal attenuation from the environment.

A conservative temperature difference of 10°C between the reservoir and the injected CO_2 was used for the modelling, as defined in D4.5. The parameter ranges applied, sourced from literature due to a lack of site-specific thermal measurements, are summarized in Table 18.

Table 18: Parameter Ranges Used for the Temperature Front Evolution Modelling.

Parameter	Minimum value	Maximum value
Rock density, (kg/m3)	2200.00	2600.00
Rock heat capacity, (J/(kg·ºK))	700.00	900.00
Well radius, (m)	0.1	0.1
Injection temperature CO_2 (ºC)	30	30
Water heat capacity, (J/(kg·ºK))	3800.00	4200.00
CO_2 heat capacity, (J/(kg·ºK))	800	1200
Joule–Thomson coefficient, (ºK/Pa)	1.00E-07	1.00E-05

The results for the lower (2.1 Mt) and upper (23 Mt) industrial injection cases are presented in Figure 20 and Figure 21.

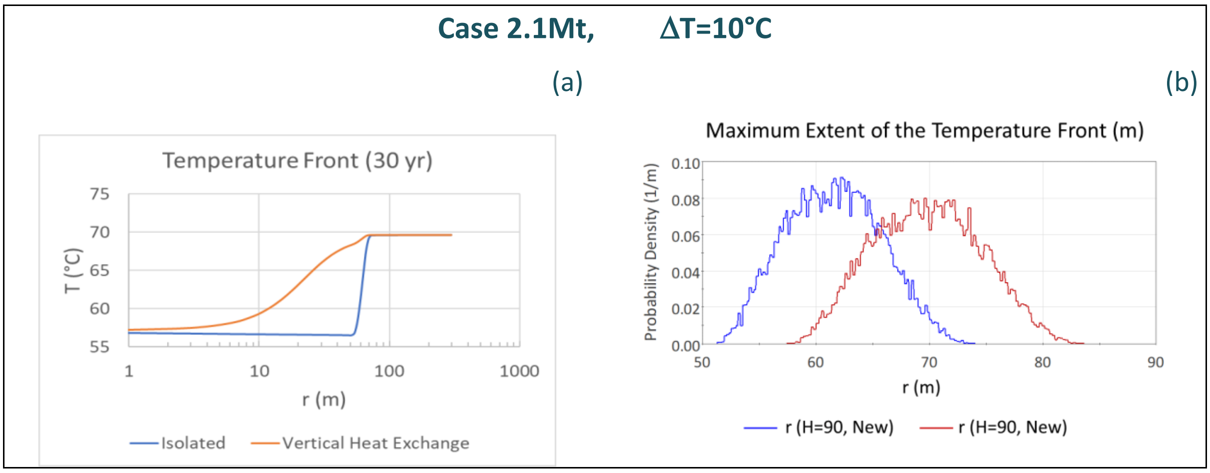

Figure 20: (a) Temperature front extent for 2.1 Mt of CO_2 injected. (b) Probability density function of the maximum temperature front extent.

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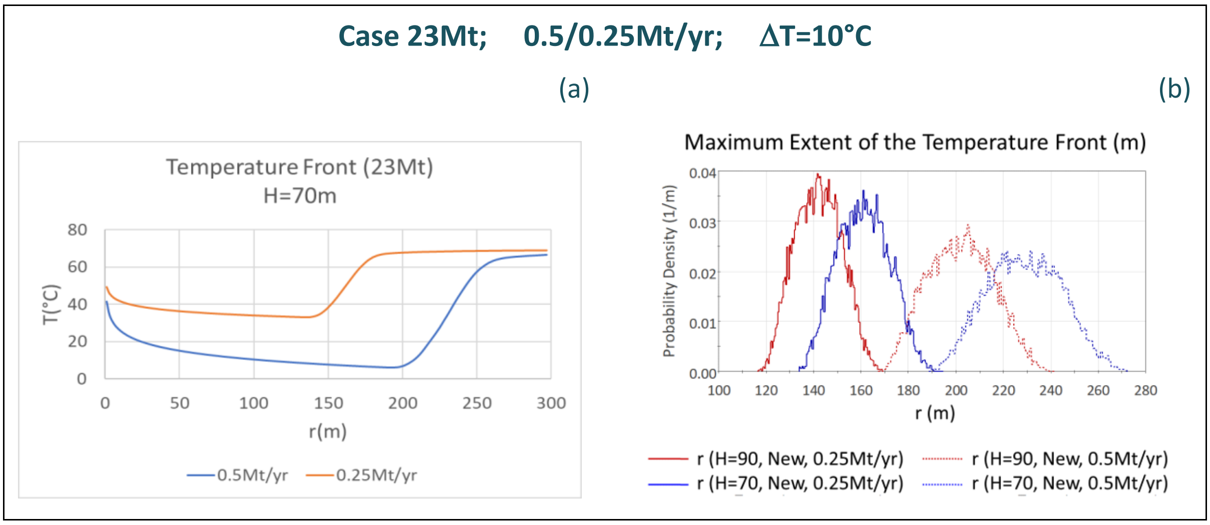

Figure 21: (a) Temperature front extent for 23 Mt of CO_2 injected. (b) Probability density function of the maximum temperature front extent.

A sensitivity analysis was performed to identify the parameters with the greatest influence on the results. The Tornado Chart in Figure 22 clearly shows that the Joule-Thomson coefficient and the rock's thermal properties (density and heat capacity) are the dominant factors controlling the extent of the thermal front.

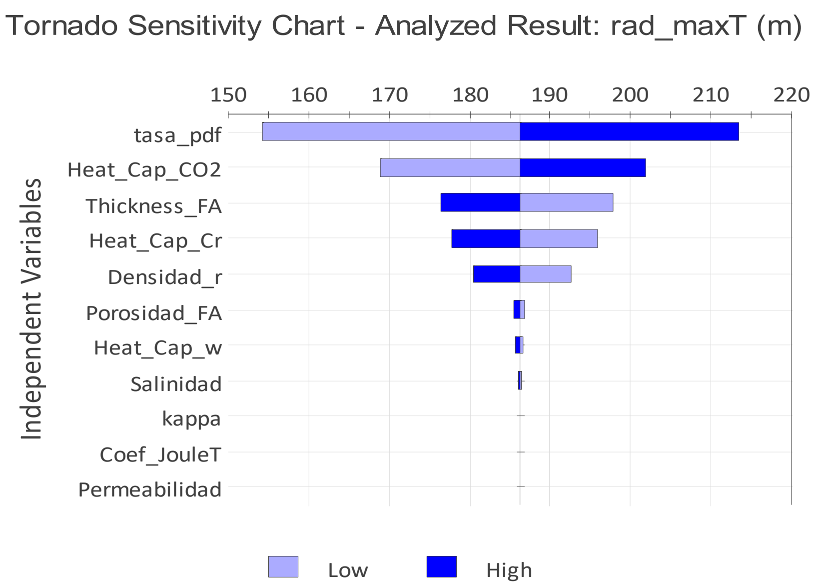

Figure 22: Tornado sensitivity chart for the temperature front extent.

4.2.3 Leakage from an abandoned well Scenario

Deep wells that penetrate the storage complex represent a potential leakage pathway, posing a risk to the long-term integrity of CO_2 storage. Assessing this scenario requires analysing the CO_2 plume extent, the integrity of well seals, and the characteristics of the surrounding formations. Figure 23 presents a schematic diagram illustrating the main causes and potential consequences associated with this leakage scenario.

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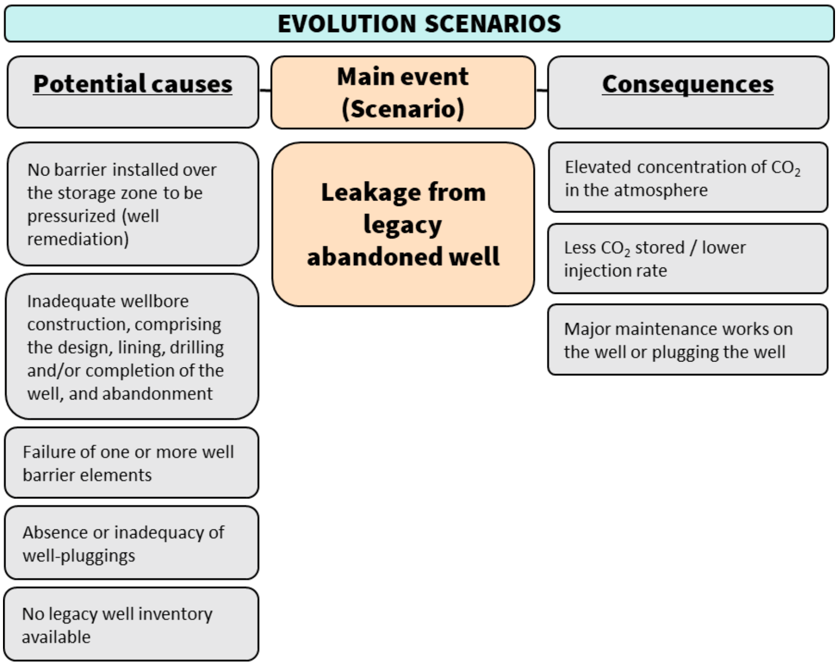

Figure 23: "Leakage from an abandoned well Scenario" including potential causes and consequences.

A critical precondition for this scenario is that the CO_2 plume must physically reach a well for leakage to occur. In order to study the potential for leakage through any existing deep wells at the Lopín site, it is worth noting that the planned location of the injection well is approximately 10 km northwest of the Lopín-1 well, which is the nearest well in the Lopín area and penetrates the Buntsandstein formation to a depth of about 32 metres. No orphaned wells have been reported in the Lopín area.

An additional factor to be considered regarding the extent of the CO_2 plume, particularly during the post-injection phase, is the potential presence of natural fluid flow within the storage aquifer. In principle, given the high salinity of the formation brine (exceeding 100000 ppm), the residence time of the connate brine is expected to be very long. This implies that, if any natural flow exists, its magnitude would likely be extremely limited. Nevertheless, no direct experimental data are currently available to confirm the existence or absence of such flow.

4.2.3.1 Results

Modelling results for both pilot and industrial-scale injection indicate that the predicted CO_2 plume does not extend sufficiently to reach the Lopín-1 well during either the injection or the long-term post-injection phase.

Plume Extent Analysis: Figure 24 shows the simulated maximum extent of the CO_2 plume for the most conservative case (injection of 23 Mt of CO_2 at 0.5 Mt/yr over 46 years), after a 1000-year post-injection period. The Monte Carlo simulations were performed under conservative assumptions that exclude the effects of residual trapping and CO_2 dissolution, which would further limit plume migration. The model also assumes the absence of significant natural groundwater flow, a premise supported by the high salinity of the formation brine, which suggests very long residence times.

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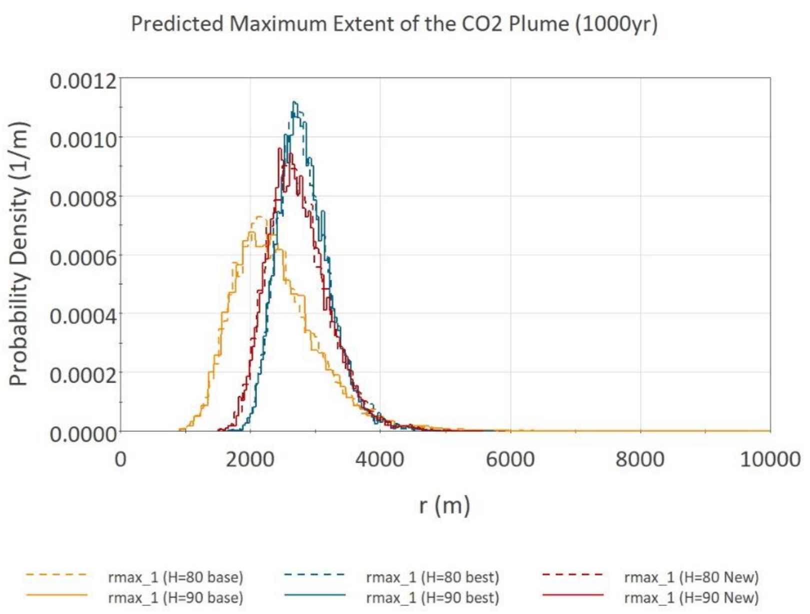

Figure 24: Predicted maximum extent of the CO_2 plume during the post-injection period (1000 years), for the injection of 23 Mt of CO_2 at a rate of 0.5 Mt/yr. The location of the Lopín-1 well is shown for context.

Consequently, it can be concluded that for both the Pilot and Industrial cases:

- **Scenario Probability:** Extremely low (effectively negligible).
- **Potential Impact:** No CO_2 leak anticipated.

4.2.3.2 Risk evaluation and recommendations

Based on this analysis, the risk of leakage from an abandoned well is evaluated as follows:

RISK SCENARIO	KEY FINDING	CONCLUSION
Leakage from an Abandoned Well	The CO_2 plume does not reach the nearest known well (Lopín-1) under any simulated injection scenario, even under conservative modelling assumptions.	✓ No risk

Recommendations:

The analysis confirms that existing wells do not pose a risk under normal storage system evolution. However, to further reinforce this conclusion, the following is recommended:

- **Hydrogeological Validation**: Conduct an experimental hydrogeological evaluation to definitively confirm the absence of significant regional groundwater flow within the Buntsandstein formation, thereby validating a key assumption of the model.

4.2.4 Leakage via existing faults

Fault zones within the storage complex represent potential conduits for CO_2 migration, posing a risk to long-term containment. Assessing this scenario requires a detailed understanding of the fault

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geometry, sealing capacity, and their interaction with the evolving CO_2 plume and pressure field. Figure 25 presents a schematic diagram illustrating the main causes and potential consequences associated with this fault-related leakage scenario.

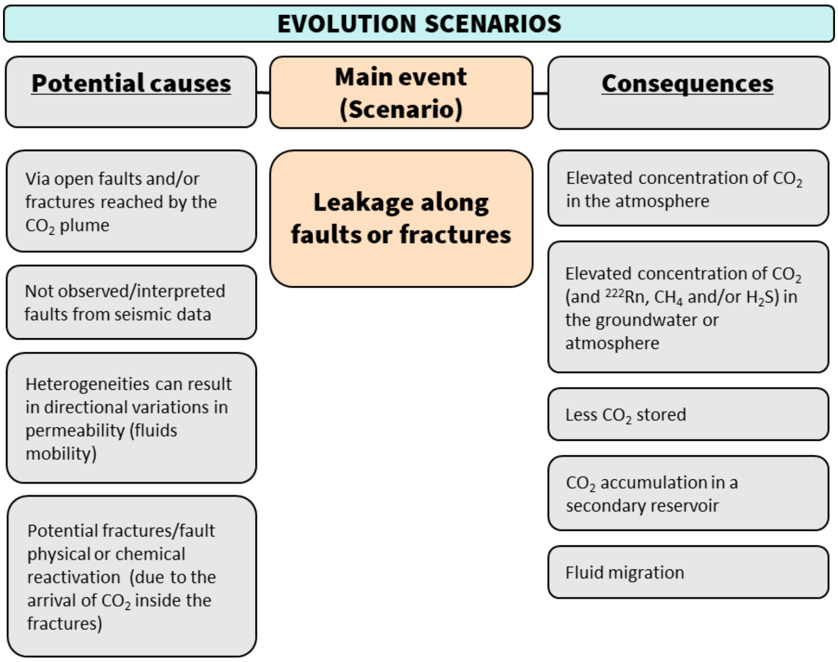

Figure 25: Scenario (3) "Leakage via existing faults" and FEPs associated, also including potential causes and consequences and their related FEPs.

The Lopín site's structural framework is defined by two main fault systems:

- NW-SE Normal Faults (Mesozoic Rift Origin): These steeply-dipping (>60°) faults, with vertical offsets up to 500 m, bound the injection horst. The planned injection point is approximately 400-600 m from these faults. While initially permeable, they may have been partially sealed by subsequent Alpine compression. They affect the Buntsandstein B1 reservoir, the B2+Röt primary seal, and the Muschelkalk M1 formation.
- NNE-SSW Alpine Reverse Faults (Compressive Origin): Inferred from seismic data, these faults are located >6 km southwest of the injection site and are considered to have low permeability due to their compressive origin. They are fossilized ~300 m below the surface, significantly reducing their potential as a direct pathway to the surface. No information is available regarding hydraulic flow, however, considering the general structural configuration of the basin, it is most likely that the flow would have a southeastward component, opposite to the inferred position of the reverse faults.

For safety assessment purposes, a potential, conservative leakage sequence is conceptualized as follows:

1. **Plume Migration to Normal Faults**: The CO_2 plume migrates from the injection point to the bounding normal faults.
2. **Upward Migration and Secondary Storage:** CO_2 ascends along the normal faults, potentially reaching the Muschelkalk M1 formation, where it could be partially trapped. For safety

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analysis purposes, the possibility of normal faults been permeable to CO_2 flow has been considered.

3. **Lateral Migration in M3**: If the normal faults cross the local M2 seal, CO_2 could reach the Muschelkalk M3 formation. Lateral migration within M3 would then be the primary mechanism, likely directed southeast, away from the reverse faults.
4. **Interaction with Reverse Faults:** For very large-volume injection, the plume in M3 could, in principle, migrate towards the distant reverse faults. However, due to their distance (>6 km), their position in relation to the regional hydrogeological flow (NW-SE), and their fossilisation by tertiary materials, they are not considered a potential risk of CO_2 emissions to the surface under pilot conditions.

The hydrogeologic behavior of this system of normal faults, presumably initially permeable but later rejugated by alpine compression, may require an individual analysis of each fault near the injection point.

4.2.4.1 Results

The risk was evaluated by combining probabilistic plume modelling with preliminary simulations of far-field migration.

Plume-Fault Interaction: Monte Carlo simulations indicate that for the **pilot injection**, the CO_2 plume is not expected to reach the normal faults. For **industrial-scale injection**, the plume is expected to intersect the normal faults (Figure 18).

Far-Field Migration Potential: To assess the consequence of this interaction, preliminary TOUGH2 simulations were run to model the extent of a CO_2 plume migrating within the M3 formation. These simulations used conservative assumptions (excluding trapping mechanisms and using low-porosity M1 formation parameters as a proxy for M3). The results show that in all analysed cases, the CO_2 plume within the M3 formation does not reach the reverse faults.

Based on this integrated analysis, the risk is evaluated as follows:

In all the analysed cases, the CO_2 plume within M3 does not reach the inverse faults. Consequently, it can be concluded that:

- Pilot case:
  - Scenario probability
    - Injection phase: The CO_2 plume does not reach the normal faults. The probability of interaction is extremely low (below 0.001%)..
    - Post-injection phase: The CO_2 plume may reach the normal faults; however, the volume of CO_2 potentially migrating into the M3 formation is very small, and the probability of reaching the reverse faults remains extremely low (below 0.001%).
  - Scenario impacts (CO_2 leak to surface) – No CO_2 leakage
  - Faults scenario do not pose any additional risk under the normal evolution conditions of the storage system.
- Industrial cases:
  - Scenario probability

    - Injection and post-injection phases: The CO_2 plume reaches the normal faults. However, preliminary simulations indicate that there is a **very low probability** of reaching the reverse faults.
  - Scenario impacts (CO_2 leak) – Low impact. In any case, there could be a diffuse leak, as the reverse faults do not reach the surface.
  - Faults scenario do not pose any additional risk under the normal evolution conditions of the storage system.

4.2.4.2 Risk evaluation and recommendations

Based on this integrated analysis, the risk is evaluated as follows:

RISK SCENARIO	KEY FINDING	CONCLUSION
Leakage via Faults (Pilot Case)	The CO_2 plume does not reach the normal faults. Even if it did, subsequent migration would not reach the reverse faults.	✓ No risk
Leakage via Faults (Industrial Case)	The CO_2 plume reaches the normal faults, but subsequent migration through the secondary system is contained within the M3 formation and does not reach the reverse faults.	✓ Very Low risk

Recommendations:

The analysis indicates faults do not pose a significant risk for the pilot phase. For future phases, the following site-specific characterisation is recommended to reduce uncertainties:

- Normal Faults near the Injection Point: Focus on determining their current permeability/sealing state, vertical connectivity, and potential for overpressure development.
- Reverse Faults: Confirm their precise location, geometry, and hydraulic properties through targeted seismic interpretation and analysis.
- Depth of reverse fault tops: ~300 m below surface; moderate uncertainty
- Hydrogeology: Characterize the natural groundwater flow regime in the Muschelkalk M1 and M3 aquifers to better constrain potential plume migration pathways.

4.2.5 Leakage through seal formation

In a geological CO_2 storage, the cap rock acts as an impermeable barrier that prevents the gas from migrating to upper layers. However, various processes can compromise this barrier, creating a risk scenario. Figure 26 presents a schematic diagram illustrating the main causes and potential consequences associated with this scenario.

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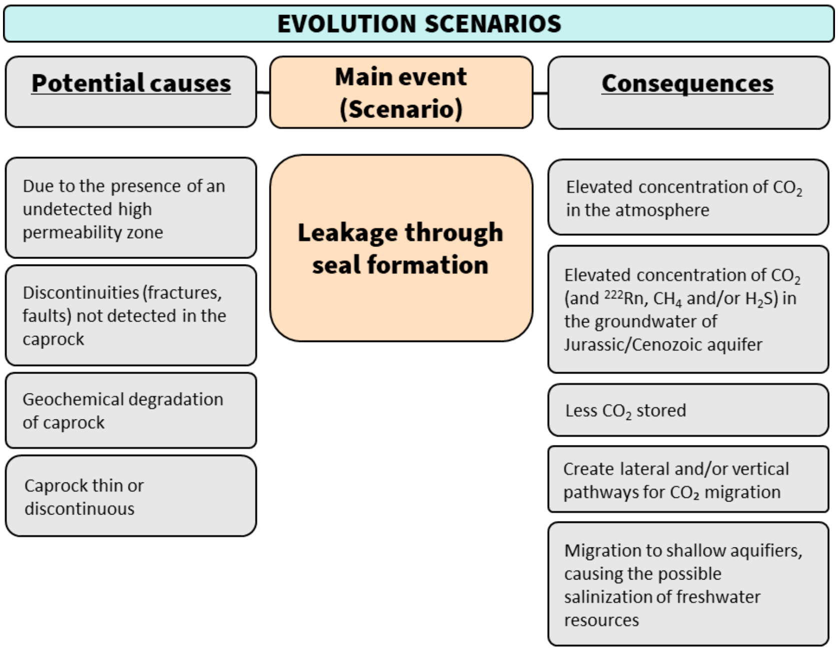

Figure 26: Scenario (2) "Leakage through seal formation" including potential causes and consequences.

The Lopín site benefits from a multi-barrier sealing system, providing a robust geological barrier against vertical CO_2 migration:

- **Primary Seal:** The Buntsandstein B2 unit and the overlying Rané Formation (Röt facies), characterized by their clay-rich composition.
- **Local Seal**: The Muschelkalk M2 unit, a sequence of Middle Triassic evaporites and shales with a thickness of 200 m in the Lopín-1 well.
- **Regional Seal:** The Upper Triassic Keuper facies, an extensive claystone unit acting as a regional aquitard, with thicknesses exceeding 500 m in the Ebro Basin.

4.2.5.1 Results

The potential for leakage has been evaluated from geochemical and geomechanical perspectives. The primary seal (the most critical element) was analyzed in detail, with findings that provide high confidence in the overall system integrity.

Geochemical Integrity

PHREEQC simulations indicate that geochemical degradation of the primary seal (Buntsandstein B2) is not a credible risk pathway. The key sealing minerals (Ca-montmorillonite, mica, chlorite) remain chemically stable (Saturation Index, SI ≈ 0) even under maximum CO_2 exposure. Furthermore, the system shows a consistent tendency for pore-clogging minerals like kaolinite (SI = 2.39–2.57) and dolomite (SI = 2.46–2.89) to precipitate, suggesting a natural "self-sealing" behavior that could enhance the seal's integrity over time.

- Conclusion: VERY LOW RISK. Geochemical processes do not represent a credible leakage pathway..

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4.2.5.1.1 Geomechanical Integrity (Caprock Fracture due to Overpressure)

The risk of mechanically fracturing the primary seal due to injection-induced overpressure was evaluated probabilistically. The analysis combines Monte Carlo simulations of pressure buildup (using the analytical models described in Section 3.2.2) with a conservative estimate of the seal rock's fracture pressure.

Quantitative Results of the Pressure Analysis

Table 19 summarizes, for different injection rates, the cumulative probability that the bottom-hole pressure remains below the fracture threshold. The key results are:

- For the pilot injection rate (0.03 Mt/yr), the probability of exceeding the fracture pressure is less than 1% across all considered petrophysical scenarios (Base, Best, New). This indicates a negligible geomechanical risk for the demonstration phase.
- For industrial injection rates, the risk becomes highly sensitive to reservoir permeability, as shown by the wide variation in probabilities in Table 19.

Table 19: Probability of Seal Fracture due to Overpressure

Injection Rate (Mt/yr)	Permeability-Porosity Reservoir Case	Cumulative Probability (Pressure < Fracture Threshold)
0.03 (Pilot)	Base	> 99%
	Best / New	~100%
0.204	Base	~55%
	Best / New	> 95%
0.5	Base	~19%
	Best / New	~45-91%

Figure 27 synthesizes the result of the integrated probabilistic analysis (pressure + strength) for the pilot case. This probability density function does not represent pressure itself, but the distribution of the *calculated risk level*. Its pronounced peak in the "Small" risk category confirms that the vast majority of plausible geological parameter combinations lead to a very low fracture risk. The tail of the distribution extending towards higher risk categories represents extremely unlikely and pessimistic parameter combinations.

Integration into the Systemic Risk Model (Bayesian Belief Network)

The aforementioned quantitative geomechanical results were integrated, along with other qualitative and quantitative evidence developed in this report, into the project's Bayesian Belief Network (BBN). This additional evidence includes, for example, the geochemical modelling results indicating a self-sealing tendency (Section 4.2.2.1), the assessment of the lateral continuity of the sealing formations, and expert judgement on the robustness of the multi-barrier system (primary, local, and regional seal). The BBN evaluates the storage complex as a system of interconnected components. The state of the "Caprock" node in the BBN (Figure 28) does not solely reflect the overpressure fracture risk. It represents the integral security state of the seal, also incorporating:

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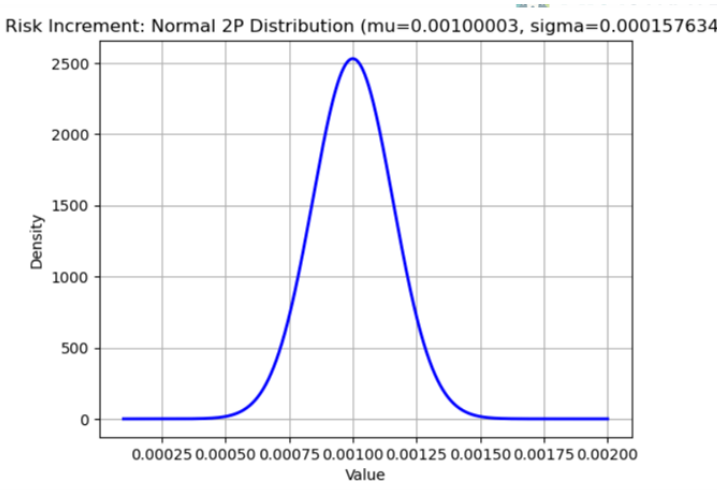

Figure 27: Probability density function of the increased risk of caprock fracture associated with increased pressure due to CO_2 injection.

1. The inherent uncertainty in the available characterization data.
2. The consideration of other potential failure modes (e.g., diffusive migration through the matrix, presence of natural fractures).
3. The probabilistic influences from other system nodes, such as "Reservoir Pressure".

Figure 28: Update of the probability values of the CapRock element in the Bayesian network, where 1 means safe conditions

The BBN result (Figure 28) shows a 71.09% probability for the 'Safe' state of the seal. It is important to interpret this value with appropriate nuance, bearing in mind that:

- It does not represent the physical probability of seal failure. The direct pressure analysis (Table 19, Figure 27) has already established that probability as less than 1% for the pilot case.
- It is the measure of confidence or belief that the systemic model assigns to the seal's security state, after assimilating all available evidence and its associated uncertainties.

The remaining 28.91% distributed across the 'Medium' and 'High' states therefore represents the model's residual uncertainty and the conservative consideration of low-probability failure scenarios other than overpressure fracture. In the context of a pre-operational risk assessment integrating multiple uncertainty sources, a confidence level above 70% in the 'Safe' state constitutes a solid confirmation of the overall low-risk profile.

Therefore, the BBN output should be interpreted as a graded measure of confidence or belief in the system's state given all available evidence, rather than a direct physical probability of failure. This output is, in essence, the system-level reliability assessment generated by our risk framework. A result showing a high probability for a 'Safe' state provides a robust and favourable verdict on overall containment security, while the distribution across higher-risk states explicitly identifies the residual uncertainties and specific components that warrant focused attention or preventive risk management measures.

With the above, we can conclude the following:

- **Pilot Case: VERY LOW RISK.** The dedicated probabilistic analysis (Table 19, Figure 27) confirms that the probability of caprock fracturing due to overpressure is negligible. The whole-system perspective (BBN) corroborates this conclusion, assigning high confidence (>70%) to the seal's safe state.
- **Industrial Case: CASE-DEPENDENT RISK**. The risk critically depends on the actual reservoir properties and the injection rate. While the "Best" and "New" cases indicate low risk, the conservative "Base" case highlights that, without more specific data to reduce uncertainty, industrial-scale rates could pose a moderate risk, making active pressure management essential.

4.2.5.2 Risk evaluation and recommendations

The presence of multiple, competent seals, combined with favorable geochemical and (for the pilot phase) geomechanical conditions, results in an overall very low risk of leakage through seals.

RISK SCENARIO	KEY FINDING	CONCLUSION & LIKELIHOOD
Leakage through Seal Formation (Pilot Case)	Geochemical self-sealing. Minimal overpressure risk.	**Very Low Likelihood.** Leakage is highly improbable.
Leakage through Seal Formation (Industrial Case)	Geochemical self-sealing. Overpressure risk is manageable and depends on reservoir properties.	**Low to Moderate Likelihood.** Leakage is unlikely, but requires careful pressure management based on the reservoir case.

Recommendations:

1. **Geomechanical Data Acquisition**: Conduct laboratory tests on seal rock samples to determine the precise fracture pressure and reduce uncertainty in the geomechanical model.
2. **Pressure Management Strategy**: Implement a robust monitoring and pressure management plan, especially for future industrial-scale injection, to ensure bottom-hole pressure remains within the safe window defined for the "Base Case" reservoir properties.
3. **Advanced Modeling:** Develop a coupled geomechanical-reactive transport model to better quantify the "self-sealing" effect and its impact on long-term seal integrity.
4. **Native Brine Geochemistry:** Confirm the geochemical findings by running PHREEQC simulations with the native high-salinity brine composition.

4.2.6 Induced seismicity scenario

The injection of CO_2 can alter the subsurface pressure and temperature fields, potentially affecting the mechanical stability of pre-existing faults and fractures. While induced seismicity typically involves microseismic events undetectable at the surface, the potential for creating new fracture pathways

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warrants careful assessment. Figure 29 illustrates the main causes and potential consequences associated with this scenario.

The Lopín storage complex is located within an extensional tectonic domain characterized by a system of NW–SE trending faults that define horst and graben structures. The injection interval corresponds to the Buntsandstein B1 formation, a moderately thick (20–70 m) sandstone unit with relatively low permeability, which acts as the main storage reservoir.

Above this level, the Buntsandstein B2 and Rané formations (Röt facies) constitute the primary seal, while the Muschelkalk M1 formation provides a secondary sealing unit. The structural configuration is dominated by steeply dipping (>60°) normal faults that crosscut the reservoir and locally affect the overlying sealing formations. These faults are aligned with the current maximum horizontal stress direction (NW–SE), which makes them potentially sensitive to pressure variations induced by CO_2 injection.

The stress regime in the Lopín area is mainly normal in the deeper section, transitioning to a strike-slip regime at shallower depths. Under these conditions, fault stability depends strongly on pore pressure evolution, rock strength, and the mechanical contrast between the reservoir and the sealing units.

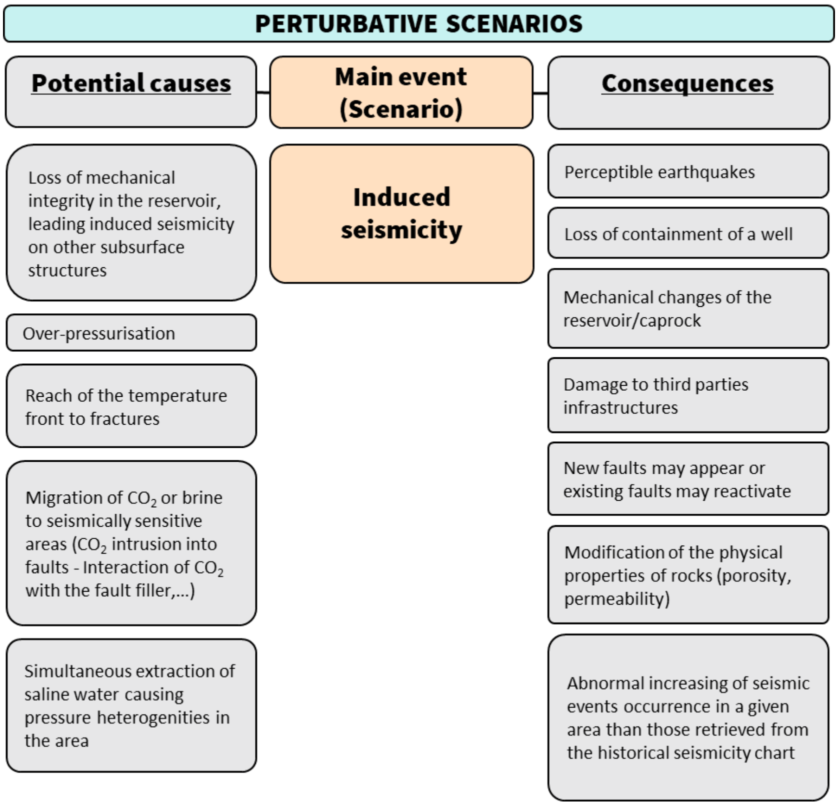

Figure 29: Scenario (4) "Induce seismicity" including potential causes and consequences.

Given the brittle nature of the fault zones and the overpressured conditions of the deep aquifer, the potential for induced seismicity is mainly associated with the reactivation of pre-existing discontinuities when fluid pressure approaches or exceeds the local failure threshold.

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Overall, the geomechanical configuration of Lopín suggests that the potential for induced seismicity is primarily linked to the reactivation of steeply dipping normal faults within the Buntsandstein reservoir interval. The presence of multiple sealing formations (B2–Rané and M2) and moderate injection pressures mitigates the risk of large-magnitude seismic events, though local slip may occur if overpressures exceed the in-situ stress margin.

4.2.6.1 Results

A geomechanical analysis was conducted to evaluate fault reactivation potential due to CO_2 injection, considering both pressure increase and thermal effects from injecting cooler CO_2. This assessment was subsequently validated and refined by independent 3D fault modeling from WP3 (Deliverable D3.5, 2025), providing a comprehensive risk perspective. The methodology and key findings are summarised below:

- Stress Regime Context: The Lopín storage complex at injection depth (1,760 m) is in a normal faulting stress regime ($S_v > S_{Hmax} > S_{hmin}$), which is generally favorable for storage. However, WP3's analysis (Deliverable D3.5, 2025) revealed the system is initially near-critical due to existing overpressure, making fault stability highly sensitive to pressure increases.
- Pressure-Only Scenario (Isothermal): The safety margin against fault slip was quantified by coupling stress regime limit equations with Monte Carlo simulations of pressure increases. This provided probabilistic distributions for the tensile strength margin becoming negative.
- Combined Pressure-Thermal Scenario: While thermal effects showed potential to reduce stability margins in theoretical calculations, the predicted extent of the thermal front (Section 4.2.2.4) indicated negligible impact for the pilot phase, justifying an isothermal assumption for this specific operational scenario.

Probabilistic Results:

To obtain the tensile-stress margins, the stress-regime limit equations were combined with the Monte Carlo–based pressure-increase distributions. The margins were calculated by subtracting the probabilistic CO_2-induced pressure increases from the corresponding stress limits. Negative margins indicate conditions under which fault reactivation may occur.

For the pilot case (0.03 Mt/year), negative safety margins occur only in the base permeability case with ~5% probability, as shown in the probability density function for tensile strength margin (Figure 30). Industrial-scale scenarios show significantly higher probabilities, strongly dependent on reservoir properties (Table 20).

The independent geomechanical analyses from WP3 (Deliverable D3.5, 2025) provide robust validation and complementary insights. Bringing together both geomechanical approaches highlights the following methodological synergies:

- Fault Representation: Radial symmetry models efficiently identify systemic pressure risks, while WP3's 3D modeling provides granular, fault-specific stability assessments
- Friction Angle Sensitivity: The 30° angle used in WP5 modelling is based on the typical values for unaltered fault surfaces found in the literature (Rutqvist, 2012). A thorough analysis of WP3 (20°, 25° and 30°) highlights the sensitivity of the system's behaviour to this parameter.
- Injector-Specific Analysis: Probabilistic treatment of injectors as equivalent enabled system-level screening. WP3's finding of higher reactivation potential around LOC-D (WP3 injection

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scenarios: CCS-1 (Case 1), LOC-D (Case 2), and simultaneous injection from both wells (Case 3)) provides essential input for detailed well placement optimization.

- Probabilistic Framework: A key synergy lies in the treatment of site uncertainty. The probabilistic approach of WP5 inherently integrates the full range of porosity and permeability variation (through their probability density functions). Consequently, the discrete P10, P50, and P90 reservoir cases defined in WP3 are not standalone scenarios but are encompassed within the probabilistic results of WP5. This provides a comprehensive risk perspective, ranging from specific deterministic cases (WP3) to the full probability distribution of outcomes (WP5).

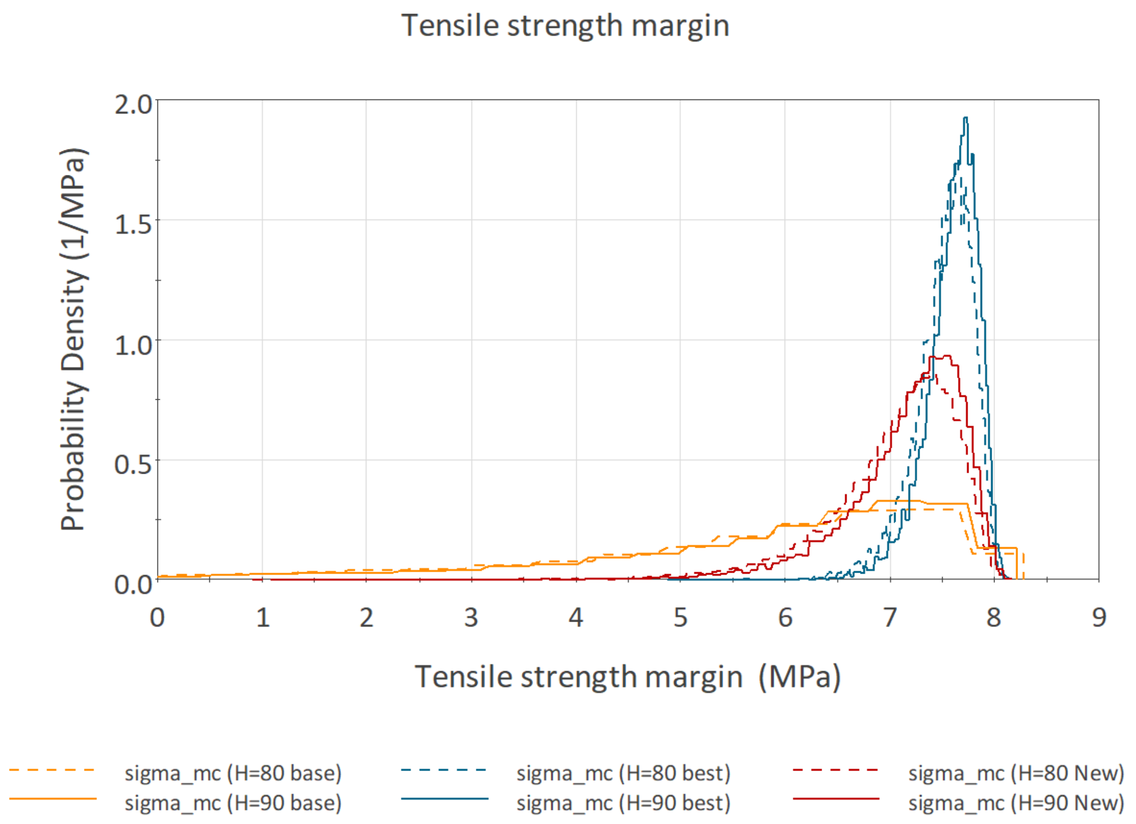

Figure 30: Pilot Case: Tensile strength margin

Both methodologies converge on the fundamental conclusion that pressure management is the dominant risk at industrial scale. WP5 assessment provides probability distributions for system-level risks, while WP3 delivers deterministic thresholds for specific fault segments and well locations.

These integrated findings confirm that while the pilot phase presents very low geomechanical risk, industrial-scale deployment requires the complementary application of both probabilistic screening and detailed geomechanical modeling within a comprehensive risk management framework.

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Table 20: Probability of Tensile strength margin<0

Injection Rate (Mt/yr)	Permeability-Porosity Reservoir Case	Cumulative Probability (Tensile strength margin<0)
0.03 (Pilot)	Base	~<5%
	Best / New	0%
0.204	Base	~70%
	Best / New	<5% / ~30%
0.5	Base	>90%
	Best / New	>65%

4.2.6.2 Risk evaluation and recommendations

The risk is highly dependent on operational parameters, specifically the temperature of the injected CO_2.

RISK SCENARIO	KEY FINDING	CONCLUSION
Induced Seismicity (Pilot/Industrial Case with pre-heated CO_2)	A positive safety margin is maintained when thermal effects are mitigated, making fault reactivation unlikely.	LOW RISK
Induced Seismicity (Industrial Case with cold CO_2 injection)	The combined pressure and thermal effects can induce localized seismic activety (fracture slip) near the wellbore, although such events are expected to be of low magnitude, since the seismic magnitude is directly related to the area of the slipping fault. In this case, the thermal effect forms only a limited halo around the well, meaning that only very small fractures could be reactivated, releasing correspondingly small amounts of energy.	MODERATE RISK (Mitigable)

Recommendations:

1. **Conduct a Technical-Economic Evaluation of Thermal Management.**

   The model identifies a mitigable risk from the thermal contrast between the injected CO_2 and the reservoir, which is expected to be less than ten degrees. A focused assessment is needed to determine if pre-heating is justified. This study should:

   - **Evaluate the geomechanical necessity** by reviewing evidence from comparable projects on whether such small thermal contrasts have a negligible impact.
   - **Analyze the cost and feasibility** of pre-heating, balancing the safety benefit against the added operational expenditure, energy use, and system complexity.
   - **If warranted, define the optimal injection temperature** that ensures a positive safety margin at a reasonable cost, avoiding unnecessary over-design.

2. **Refine the Geomechanical Model with Coupled THM Simulations.** To reduce uncertainty and better quantify the risk, advanced modeling should be performed to:
   - Precisely delineate the volume of rock affected by thermal stresses.

- Provide a more robust estimation of potential seismic magnitudes, helping to confirm the predicted low-impact nature of any induced events.

3. **Implement a Microseismic Monitoring Baseline and Plan**. Prior to injection, establish a sensitive monitoring network to:
   - Characterize the background seismicity of the site.
   - Detect and locate any microseismic activity during operations, verifying model predictions and ensuring early awareness.
   - Serve as a trigger for a pre-defined contingency plan if event magnitudes were to exceed forecasted levels.

4.2.7 Global Assessment. Risk Assessment Methodology Based on Bayesian Networks

Bayesian Belief Networks (BBNs) are probabilistic graphical models that represent a set of variables and their conditional dependencies via a directed acyclic graph. In the context of geological storage risk assessment, BBNs provide a structured framework to combine diverse data types—from quantitative numerical models to qualitative expert judgment—into a unified risk model (Pearl, 1988)].

For the Lopín site, the BBN was initially constructed exclusively using Expert Judgment (EJ). This approach was strategically chosen to provide a preliminary risk assessment from the project's outset, enabling risk-informed guidance for early decision-making despite the absence of extensive quantitative data. In this early stage, a machine learning approach was not feasible due to the lack of a sufficient historical dataset. The expert-driven BBN served as the foundational, qualitative risk model, establishing a clear baseline and identifying key uncertainties.

The implemented BBN structure for Lopín (Figure 31) reflects the main components of the storage complex (reservoir, seals, faults, wells) and their interrelationships, allowing for an integrated analysis of potential leakage pathways.

The methodology is inherently adaptive. The initial, qualitative estimates populating the model are designed to be systematically updated and replaced by hard data from site-specific characterization (e.g., core analysis, seismic interpretation) and dynamic simulations (e.g., plume migration models) as the project advances (Hurtado et al., 2014). This iterative process ensures the risk assessment evolves alongside the project's maturity.

The expert-derived BBN systematically addresses the key risk scenarios identified in Section 4.2:

- CO_2 leakage through existing wells
- Leakage due to seal fracturing from overpressurization
- Leakage through the seal's porous matrix
- Leakage through geological faults

The transition from a qualitative to a quantitative framework was achieved through a rigorous process of probabilistic analysis using analytical models and Monte Carlo simulations, executed using the GoldSim© platform. This approach was critical for two reasons: firstly, analytical models could be run a sufficiently high number of times (hundreds of thousands of iterations) to robustly characterize the uncertainty and generate meaningful Probability Density Functions (PDFs) for key parameters.

Secondly, this provided a computationally efficient method to populate the BBN with quantitative, probabilistic inputs derived from physics-based models, rather than relying solely on expert estimates.

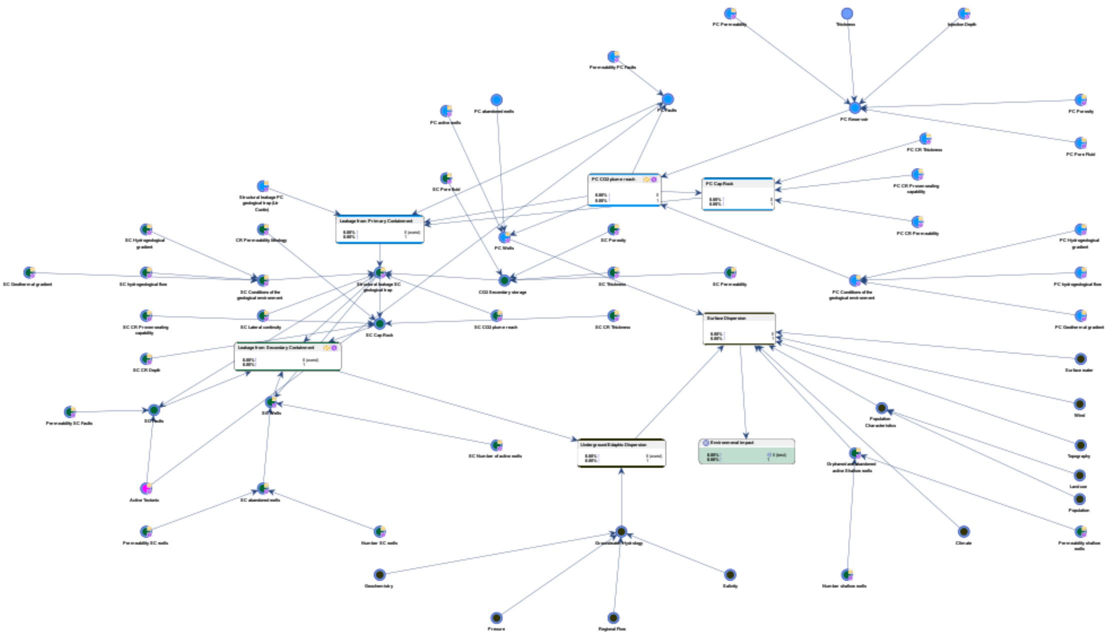

Figure 31: Expert-derived Bayesian Belief Network structure for the Lopín site risk assessment.

Key outputs, such as the maximum plume extent, were characterized using the resulting PDFs (Figure 32). Figure 32a shows the histogram and fitted probability density function (PDF) for the maximum plume extent. Figure 32b is a complementary probability plot used to validate the assumption that the data follow a lognormal distribution. The close alignment of the data points (blue) along the 45-degree theoretical line (red) confirms that the lognormal distribution with parameters mu=4.3383, sigma=0.204, gamma=136.898 is a statistically robust model for this output.These distributions were then integrated into the BBN to define risk levels based on the distance from potential leakage elements (Figure 33), formally moving the model from a purely qualitative to a semi-quantitative state.

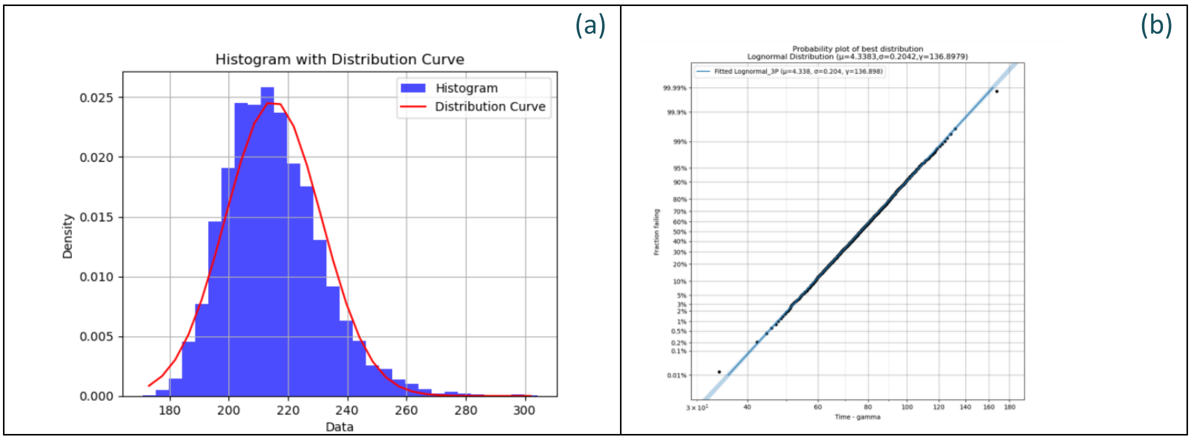

Figure 32: a) Probability density function for maximum plume reach, derived from Monte Carlo simulations in GoldSim (GoldSim 2025); b) Complementary probability plot shows that the data follows a lognormal distribution.

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```
Percentiles defining risk levels:
Very Low Risk: Above 0.99 percentile
Low Risk: 0.99 to 0.90 percentile
Medium Risk: 0.90 to 0.50 percentile
High Risk: 0.50 to 0.10 percentile
Very High Risk: Below 0.10 percentile
Results:
Probability that x > 1750: 0.0000
Risk Level: Very Low
```

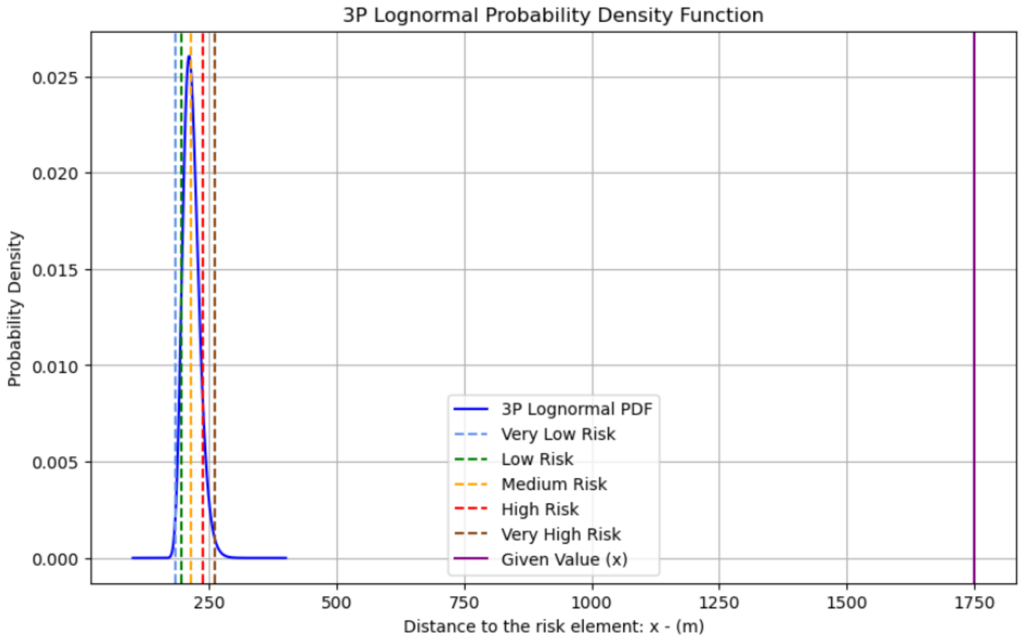

Figure 33: Risk level classification based on distance to potential leakage pathways.

The core strength of this approach is its demonstrated capacity for dynamic updating. The integration of initial simulation results into the BBN is captured in Figure 34, which compares the initial expert-based assessment with the updated profile. It is important to note that the probabilities shown in this figure (e.g., '71.09% Safe' for Caprock) represent the model's degree of belief or confidence in each state, derived from assimilating all input evidence and their uncertainties. They should not be interpreted as direct physical probabilities of failure, which are derived from specific, targeted analyses (such as the geomechanical probability of fracture shown in Table 19).

This progression validates the chosen methodology. Should the project move forward, the framework is explicitly designed for a future transition to a fully quantitative, data-driven model. Enhanced site characterization and operational monitoring data will enable the application of machine learning techniques to further refine the network's structure and parameters, transforming the BBN into a continuously learning tool that provides an increasingly robust safety case throughout the project's lifecycle.

Synthesis in a Hybrid Quantitative-Qualitative Model

The final strength of the implemented Bayesian Belief Network lies in its role as a hybrid quantitative-qualitative model. While key dynamic parameters, such as plume extent and pressure buildup, were quantified through probabilistic simulations, other critical factors inherently remained qualitative.

These included assessments of the structural integrity of legacy wells or the long-term geochemical reactivity of the seal, which are difficult to reduce to a single numerical value at this stage. The BBN

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successfully integrates these diverse data types, allowing quantitative PDFs and qualitative expert ratings to coexist and interact within the same probabilistic framework.

This synthesis provides a comprehensive risk portrait that would be impossible with a purely quantitative approach, ensuring that critical, yet unquantified, expert knowledge is systematically incorporated into the final safety assessment.

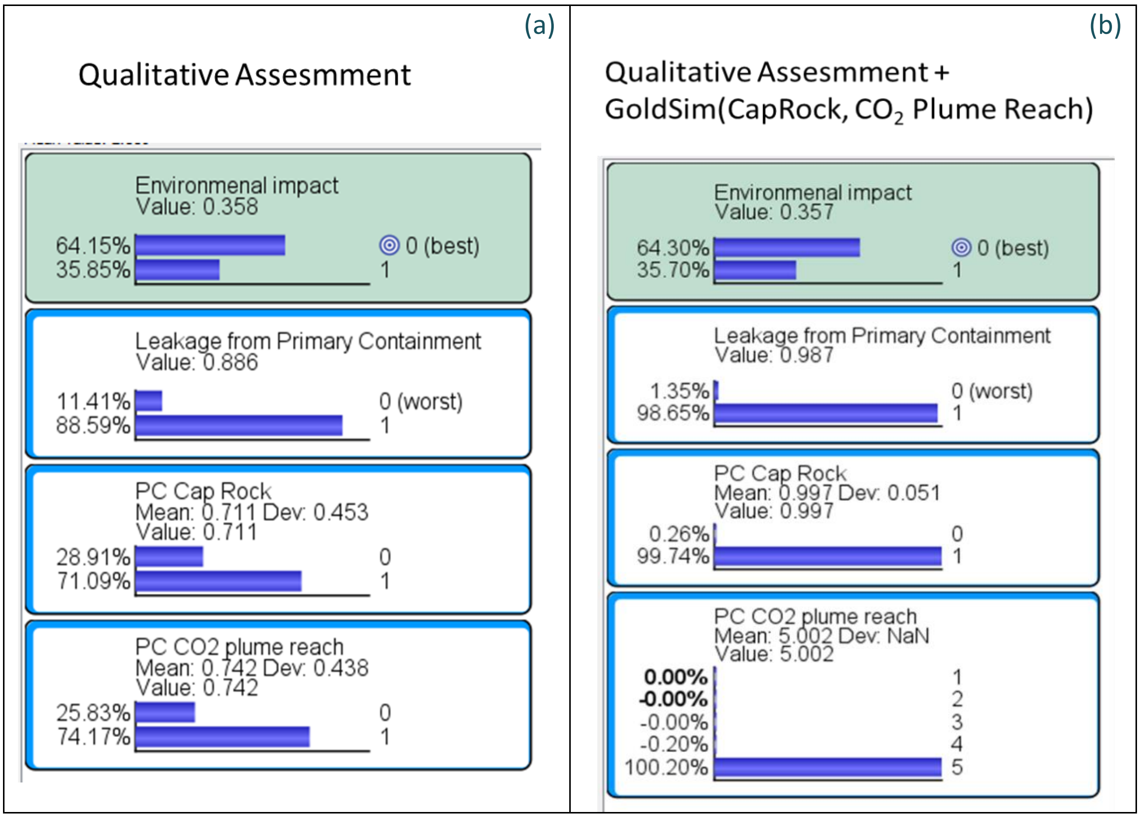

Figure 34: Evolution of the risk assessment: (a) initial expert-based (qualitative) analysis and (b) updated analysis incorporating initial plume and pressure modeling results.

4.3 Risk analysis synthesis

The detailed, technical risk analysis for individual scenarios was synthesized into a comprehensive Project Risk Register. This process ensured that all identified risks were managed systematically throughout the project lifecycle, with the objective of increasing the probability of project success by minimizing the impact of threats.

The synthesis was conducted through a structured workshop involving multiple work packages, utilizing a risk management platform developed by Repsol. This collaborative approach allowed for a consistent evaluation of risks across different domains (e.g., Political, Economic, Social, Legal, Technological).

For the environmental and safety risks under the scope of WP5—the focus of this report—the assessment of impacts on human health and the environment specifically adhered to the guidelines outlined in the CCS Guidance Document 1 " CO_2 storage life cycle and risk management framework."

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A key aspect of this synthesis for the WP5 risks was the translation of quantified risks into the project's qualitative framework. The probabilistic results for environmental and safety scenarios—derived from Probability Density Functions (PDFs) and Bayesian Belief Networks—were meticulously mapped onto the standardized Probability-Impact matrix. This translation was necessary to integrate these quantitatively-derived risks with other project risks that are inherently qualitative at this stage, ensuring a consistent and comprehensive overview in the global Project Risk Register.

Risks were subsequently categorized and qualitatively analyzed using a standard Probability-Impact matrix, with ratings from Very Low to Very High. For each identified threat, a specific risk response and mitigation measure was defined. The effectiveness of these measures was then evaluated by assessing the residual risk after their implementation.

The final WP5 Risk Register for the Lopín pilot is summarized in Figure 35, which shows the risk map for the current situation (Before Response) and the projected situation after applying the proposed mitigation measures (After Response).

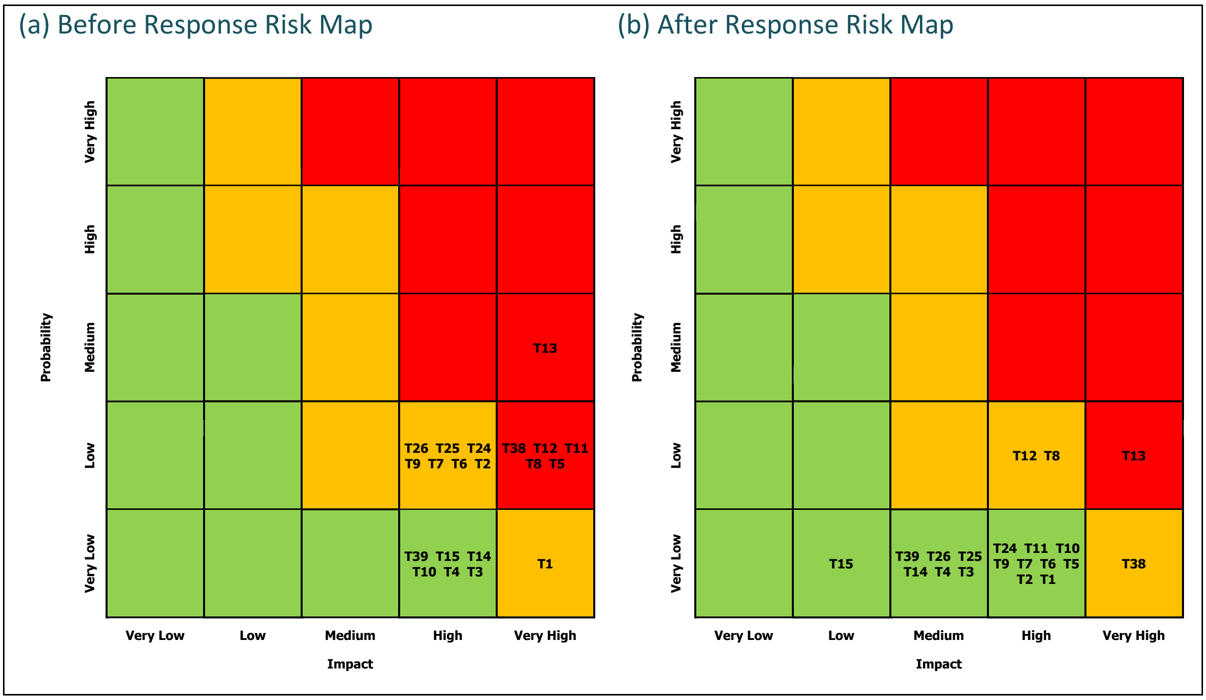

Figure 35: Comprehensive risk matrices for the Lopín site, showing the initial risk assessment (a) and the residual risk after the application of threat responses and mitigation measures (b).

The register encompasses a wide range of threats (T), categorized primarily as Environmental & Safety (EN) or Technological (T), as detailed in the Table 21.

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Table 21: WP5 Threat Register for Lopín site

Cod.	Threat/Opportunity	Cat.	Scenario
T1	T	EN-Environmental & Safety	Vertical leakage through caprock (sealing deficiency)
T2	T	EN-Environmental & Safety	Vertical leakage along faults or fractures
T3	T	EN-Environmental & Safety	Structural spill
T4	T	EN-Environmental & Safety	Lateral leakage
T5	T	EN-Environmental & Safety	Leakage from operating well
T6	T	EN-Environmental & Safety	Leakage from legacy abandoned well
T7	T	EN-Environmental & Safety	Migration of formation brine outside expected boundaries
T8	T	EN-Environmental & Safety	Induced seismicity
T9	T	EN-Environmental & Safety	Disruption by a later activity
T10	T	EN-Environmental & Safety	Changes in groundwater flow, within the reservoir or in other layers of the storage complex
T11	T	T-Technological	Loss of Injectivity
T12	T	T-Technological	Lower than expected capacity
T13	T	T-Technological	Unexpected compartmentalization
T14	T	T-Technological	Accidental Over-fill
T15	T	EN-Environmental & Safety	Uplift or subsidence of ground
T24	T	EN-Environmental & Safety	Unforeseen CO_2 impacts
T25	T	EN-Environmental & Safety	Conflicts with other subsurface or surface land uses
T26	T	T-Technological	Unexpected variations in CO_2 composition
T38	T	T-Technological	Fracturing of the caprock induced by injection
T39	T	EN-Environmental & Safety	Natural seismicity

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Key Outcomes of the Risk Synthesis:

- Initial Risk (Before Response): The analysis identified several high-priority (red) risks requiring immediate attention, including unexpected compartmentalization (T13), fracturing of the caprock (T38), lower than expected capacity (T12), induced seismicity (T8), and leakage from an operating well (T5).
- Residual Risk (After Response): The application of specific mitigation measures—such as the phased injection strategy, robust MMV plan, and well integrity protocols—demonstrates a significant overall risk reduction. The number of high-priority (red) risks is reduced to a single item (T13 - Unexpected compartmentalization), which will be a key focus for further characterization. Most other high and medium risks are successfully downgraded to low (green) or moderate (yellow) levels.

This synthesis confirms that the proposed risk responses and mitigation measures are highly effective in managing the identified threats. This substantiates the overall safety case for the Lopín pilot project.

The integrated risk assessment, represented through the Bayesian Belief Network, provides a clear indication of the reliability of the system at the Lopín site. For the pilot phase, this verdict is strongly positive, indicating a high level of confidence in 'Safe' states and confirming the site's robustness. Furthermore, the model highlights that achieving industrial-scale viability will depend primarily on reducing uncertainties related to reservoir permeability and fault seal integrity—key components identified for focused preventive management.

4.4 Analysis of Consequences and Implications for Scalability

This risk assessment concludes that the likelihood of CO_2 leakage or other significant safety impacts during the pilot phase is negligible, precluding a meaningful quantitative distribution of such classic risk consequences. The dominant risk for the Lopín site is instead one of performance and economic value: the uncertainty in reservoir properties does not significantly alter the probability of failure, but it has a drastic and quantifiable impact on the project's achievable value. Therefore, this section addresses the requirement for a quantitative analysis of consequences by evaluating the impact of geological uncertainty on the project's fundamental value proposition—its storable volume and economic viability—rather than on low-probability failure events.

The qualitative and probabilistic risk assessment confirms the very low-risk profile of the pilot phase and identifies the key uncertainties for industrial-scale deployment. To translate these technical findings into a decision-making framework, this section quantifies the consequences of the dominant risks using metrics relevant to project economics and strategic planning. The goal is to articulate the tangible value of risk mitigation and the potential cost of inaction.

4.4.1 Dominant Uncertainty: The Impact on Storage Capacity

The probabilistic analysis identifies reservoir permeability as the single most critical uncertainty controlling the system's industrial-scale behaviour. This uncertainty is not merely a technical parameter; it has a direct and quantifiable impact on the project's fundamental value proposition: its storable volume.

The divergence in projected performance between the different reservoir cases is extreme. For a single-well, 30-year injection scenario designed to remain within the safe geomechanical pressure

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limit (~30.5 MPa), the analysis reveals (see Section 3.4, Figure 13, and Section 4.2.2**Erreur ! Source du renvoi introuvable.**):

- Base Case (Initial Characterization): The maximum storable volume is approximately 1.8 Mt. This scenario is derived from the initial, conservative petrophysical data set (Section 3.2.1, Table 1).
- New Data / Best Case (Improved Characterization): The maximum storable volume under identical safety constraints is approximately 13.8 Mt. This scenario is based on the refined petrophysical distributions incorporating data from the CHIPRANA-1 well (Appendix 8.3.1).

This comparison quantifies the "Risk of Underperformance" in the most critical metric for a storage site: its capacity. The prevailing geological uncertainty translates into a potential loss of over 12 million tonnes of storable CO_2 for a single well. This "capacity gap" of more than 85% underscores that the decision to invest in further characterization is not a pure cost, but a strategic investment to unlock the site's full potential and economic viability. This approach aligns with established principles of Value of Information (VOI) analysis, where spending to reduce key uncertainties can dramatically increase expected project value (Bratvold et al., 2009).

This risk can be expressed in economic terms. Assuming an estimated cost of €15 million for a dedicated characterization well, securing the additional 12 Mt of capacity would be economically justified even if it only resulted in a long-term storage cost saving of approximately €1.25 per tonne. This breakeven cost of ~€1.25/t represents only a small fraction of typical storage-related costs. Various studies and reviews show that storage (and transport+storage) costs are highly site-dependent and can range from a few dollars up to several tens of dollars per tonne of CO_2, with many U.S. estimates clustering around USD 7–13/t for onshore saline formations (see e.g. IEA, 2020; DOE-derived estimates summarized in Net Zero analyses). This makes the investment in characterization highly compelling as an inexpensive insurance policy for project value.

4.4.2 Qualitative Cost-Benefit Analysis of Key Risk Mitigations

For other key risks, where a direct volumetric metric is not applicable, a qualitative analysis of the "cost of mitigation" versus the "cost of failure" provides a framework for prioritisation (see Table 22).

Table 22: Risk Consequence and Mitigation Cost Analysis

RISK SCENARIO	CONSEQUENCE / "COST" OF FAILURE	MITIGATION MEASURE & APPROXIMATE COST
HIGH UNCERTAINTY IN RESERVOIR PERMEABILITY	Drastic reduction in storable volume (>12 Mt loss). Inability to justify industrial-scale investment.	**High Cost:** Drilling of a dedicated characterisation well.
INDUCED SEISMICITY (INDUSTRIAL CASE WITH COLD CO_2)	Project suspension, reputational damage, regulatory intervention, potential for minor infrastructure liability.	**Moderate-High Cost**: CAPEX/OPEX for a CO_2 pre-heating system and enhanced microseismic monitoring.
CAPROCK FRACTURE / SEAL FAILURE	Catastrophic containment failure, project termination, severe legal and	**Moderate Cost:** Implementation of a robust, adaptive MMV plan and

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	financial liabilities, environmental damage.	pressure management strategy.
LEAKAGE VIA ABANDONED WELLS	Loss of containment, regulatory non-compliance, financial penalties, project closure.	**Negligible Cost:** The analysis shows the risk is negligible; no mitigation is required.

This analysis shows that the most critical investment is in resolving the reservoir uncertainty. The cost of a characterisation well is likely orders of magnitude lower than the economic value of the storage capacity it could unlock. Similarly, the cost of mitigating induced seismicity through pre-heating is a manageable insurance policy against a high-impact, project-stopping event, a concept central to proactive risk management in subsurface engineering (Aven & Renn, 2009).

4.4.3 Decision Pathway for Project Scaling

The findings can be synthesised into a clear decision pathway for transitioning from pilot to industrial operation, illustrating the strategic importance of a phased, risk-informed approach (see Figure 36).

Figure 36: Risk-Informed Decision Pathway for Lopín Site Industrial Scaling

This pathway makes it evident that the pilot phase, while confirming fundamental safety, primarily serves to identify and quantify the specific uncertainties that govern industrial scalability. Proactive investment in targeted data acquisition is thus the essential catalyst that determines the project's trajectory. Without this investment, the project remains constrained to a limited-capacity demonstration. With it, the door opens to a viable, large-scale storage operation where risks are understood, managed, and transformed into a bankable asset. The recommendations that follow are specifically designed to execute this critical de-risking pathway in the most efficient and effective manner.

4.5 Validation of the Probabilistic Risk Assessment Methodology

The probabilistic approach adopted in this study has been validated through direct comparison with the high-fidelity numerical simulations conducted in Work Package 3. As detailed in Appendix 8.3.1, this comparison demonstrates a strong consistency between the two independent methodologies in predicting both CO_2 plume migration and pressure evolution under various injection scenarios.

Key validation findings include:

- Storage Capacity Predictions: The probabilistically derived injectable masses show near-perfect alignment with the detailed model results across all scenarios (P10, P50, P90), with differences of less than 0.1 Mt.

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- Pressure Limit Validation: The injection rates defined as "limit cases" by the detailed models consistently fall in the upper tail of the pressure distribution predicted by the full probabilistic analysis, confirming their operational robustness.
- Methodological Confirmation: The probabilistic framework successfully captures the system's dominant behaviors and uncertainties, validating its application for early-phase decision-making when detailed characterization data is limited.

This successful cross-validation provides high confidence that:

1. The risk conclusions presented in this report are grounded in a methodology consistent with high-fidelity physics
2. The Bayesian Belief Network, populated with probabilistic model outputs, represents a reliable tool for dynamic risk management
3. The phased approach—using probabilistic models to guide characterization which then informs detailed models—creates a robust foundation for scaling decisions.

5. Recommendations

The following recommendations are derived from a risk assessment that concludes the Lopín site, particularly for the pilot phase, is characterized by a **low-risk profile and a robust geological system.** The detail and extent of these recommendations are not a reflection of high-probability risks, but are guided by three fundamental principles that go beyond the baseline safety case:

1. **Regulatory Due Diligence:** EU Directive 2009/31/EC and Spanish Law 40/2010 require not just a demonstration of low risk with current data, but a **predictive and robust understanding of the storage system** that guarantees long-term security. High uncertainties are themselves a regulatory concern to be actively reduced.
2. **A Pathway to Industrial Scale:** The pilot phase is safe with existing data. However, to confidently scale to an industrial operation, the current uncertainties become significant impediments. These recommendations provide the **continuous roadmap for that transition**, transforming the pilot into a critical de-risking activity.
3. **Earning Social and Regulatory License:** For stakeholders and authorities, it is insufficient to state that risks are low. Public perception, particularly regarding the potential for **induced seismicity**, demands a response that goes beyond technical probabilities. It is essential to **demonstrate active vigilance, exceptional response capability, and a transparent commitment to monitoring.** A robust Monitoring, Measurement, and Verification (MMV) plan, with a specific focus on microseismic activity, and a detailed corrective measures plan are fundamental to building this essential trust and addressing this primary public concern directly.

In summary, these recommendations are proposed to **respond to uncertainties in a proportionate and credible manner, optimize future design, and, most importantly, demonstrate to regulators and society that every reasonable effort has been made, going beyond the bare minimum.**

5.1 Future Research and Data Acquisition

The following actions are critical to reduce dominant uncertainties, not because failure is imminent, but to build a more robust, predictive safety case for the long term and for larger scales.

1. **High-Resolution Reservoir Characterization via a Dedicated Well:**
   - **Action:** Drill a dedicated characterization well at the injection site to acquire high-resolution wireline logs, side-wall cores, and conventional core samples across the entire Buntsandstein interval.
   - **Risk Justification:** Permeability and porosity are the dominant factors controlling pressure buildup. The vast difference in allowable injection rates between the "Base Case" and "Best/New Data Case" underscores that regional data is insufficient for optimizing industrial-scale operations. Location-specific data is essential to replace conservative assumptions with informed forecasts.
2. **Site-Specific Geomechanical Laboratory Testing:**
   - **Action:** Conduct a comprehensive suite of geomechanical tests on core samples from the primary seal (Buntsandstein B2/Rané) and the reservoir rock.
   - **Risk Justification:** The current fracture pressure estimate is based on a generic relationship. Site-specific data is required to define a robust Maximum Allowable Bottom Hole Pressure (MABHP), moving from a conservative guess to a precise, defensible operational limit for regulatory approval.
3. **Fault Seal and Hydrodynamic Analysis:**
   - **Action:** Perform a dedicated fault seal analysis study integrating 3D seismic reinterpretation and a review of existing pressure data.
   - **Risk Justification:** For industrial-scale injection, understanding whether these faults act as barriers or conduits is the single most important uncertainty for predicting long-term plume migration and storage capacity. This analysis is fundamental for defining the ultimate containment boundaries of the site.
4. **Advanced Coupled Process Modeling (THMC):**
   - **Action:** Develop and calibrate a detailed 3D Thermo-Hydro-Mechanical-Chemical (THMC) model.
   - **Risk Justification:** A coupled model is essential to quantitatively predict the low-probability, high-consequence scenario of fault reactivation under combined pressure and thermal stresses, providing a robust tool for demonstrating operational control to regulators.
5. **Comprehensive Induced Seismicity Monitoring and Communication Plan**
   - **Action:** Develop and implement a dedicated plan that integrates three components:
     - i. **Technical:** Install a high-sensitivity, local microseismic network *before* injection begins to establish a baseline and detect any microseismicity with high precision.
     - ii. **Protocols:** Define clear, public-facing traffic-light protocols that link specific seismic magnitudes or ground motion levels to pre-defined operational responses (e.g., reduction of injection rate, voluntary shut-in).
     - iii. **Communication:** Create plain-language materials explaining what induced seismicity is, the difference between detectable microseismicity and felt earthquakes, and how the project's protocols are designed to prevent the latter.

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- **Risk Justification:** While the geomechanical analysis indicates a very low probability of felt seismicity, public fear on this issue is disproportionate to the technical risk. This dedicated plan directly addresses this gap by demonstrating utmost caution, establishing verifiable control measures, and fostering transparency. It turns a potential public relations vulnerability into a demonstration of operational excellence and social responsibility.

5.2 Design and Operational Recommendations

Operational strategies must be tailored not just to prevent failure, but to demonstrate exemplary management and control.

1. **Implementation of a "Phased Injection with Active Pressure Management" Strategy:**
   - **Action:** Adopt a staged approach, using the pilot phase as a large-scale "Well Test" to calibrate models before any rate increase.
   - **Risk Justification:** This is the most robust strategy to manage uncertainty. It embodies the precautionary principle, turning the pilot into a proactive risk-reduction tool and building a solid empirical basis for future regulatory applications.
2. **Technical-Economic Evaluation of CO_2 Pre-heating:**
   - **Action:** Conduct a detailed study to evaluate the necessity and cost of pre-heating the injected CO_2.
   - **Risk Justification:** This addresses a mitigable, moderate-risk scenario for industrial-scale injection. The evaluation ensures that the project is prepared with an engineering control to definitively eliminate the thermal stress component, showcasing a design-to-risk approach.
3. **Robust Well Design and Real-Time Integrity Monitoring:**
   - **Action:** Design the injection well with corrosion-resistant casing and install a Permanent Downhole Monitoring System (PDHMS).
   - **Risk Justification:** This is a direct, best-practice mitigation for the "Leakage from an operating well" scenario. Continuous monitoring provides the highest level of assurance and operational control, serving as a cornerstone for the project's credibility.

5.3 Recommendations for the MMV and Corrective Measures Plan (WP4)

The MMV plan is the primary tool for building trust through transparency and demonstrated control.

1. **Tiered Monitoring Strategy with Pressure and Seismicity as Tier-1:**
   - **Action:** Implement a tiered MMV plan prioritizing downhole pressure and microseismic monitoring.
   - **Risk Justification:** This prioritizes resources towards the highest consequence risks. Pressure is the most direct indicator of containment, and **seismicity monitoring is established as a non-negotiable priority, directly addressing the foremost public safety concern and providing the essential data to validate geomechanical models**.
2. **Targeted Fluid Geochemical Monitoring as an Early Warning System:**
   - **Action:** Establish a pre-injection baseline and monitor specific ionic tracers.

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- **Risk Justification:** This serves as a secondary, scientific validation of the system's behavior, providing an early warning capability that reinforces the message of comprehensive oversight.

3. **Pre-defined, Trigger-Based Corrective Measures Plan:**
   - **Action:** Develop specific, actionable procedures with clear thresholds for response.
   - **Risk Justification:** A pre-approved plan eliminates ambiguity and demonstrates a capacity for rapid, effective response. It is a critical component of the operational license, proving that the project is not only safe but also in full control.

5.4 Other Recommendations on Legal and Regulatory Requirements

The risk assessment provides a solid foundation for a sophisticated engagement with the permitting authority.

1. **Submission of a Probabilistic Safety Case:**
   - **Action:** Structure the Storage Permit application around the probabilistic framework developed in this report.
   - **Risk Justification:** This approach is more rigorous and transparent than a deterministic "worst-case" scenario. It explicitly quantifies uncertainty and demonstrates a deeper understanding of the system, facilitating a more informed and confident regulatory review.
2. **Strategic Use of the Exploration Permit for Data Gathering:**
   - **Action:** Explicitly define the pilot injection phase within the Exploration Permit as the final stage of site characterization.
   - **Risk Justification:** This formally aligns the project with the regulatory requirement to "demonstrate" safety, framing the pilot as a mandatory de-risking activity and ensuring a smoother transition to a Storage Permit.
3. **Proactive Stakeholder Engagement Based on Risk Findings:**
   - **Action:** Use the clear, scenario-based risk evaluations as the cornerstone of public communication.
   - **Risk Justification:** Transparency is key to building trust. Addressing concerns directly with the backing of a detailed scientific assessment demonstrates a proactive safety culture and is fundamental to earning a social license to operate.

6. Conclusion

This risk assessment provides a comprehensive and quantitative evaluation of the safety and performance of the Lopín site for the geological storage of CO_2. The analysis, structured in two phases and employing advanced probabilistic methods, leads to unequivocal conclusions for the proposed pilot injection and provides a clear pathway for assessing future industrial-scale deployment.

1. Conclusive safety case for the pilot injection

The findings of this study conclusively demonstrate that the pilot-scale injection of 100,000 tonnes of CO_2 at a controlled rate of 0.03 Mt/yr presents a **very low, well-understood, and acceptable risk profile**, fully compliant with the safety objectives of the EU CCS Directive.

- **Containment assurance:** Under the proposed pilot conditions, the CO_2 plume is predicted to remain well within the storage complex, with a negligible probability of reaching the bounding faults or any existing wells. The multi-barrier seal system—particularly the robust regional Keuper seal—provides exceptional geological confidence in long-term containment.
- **Integrity of barriers:** The combined geochemical and geomechanical analyses confirm the competence of the seal. The risk of caprock fracturing from overpressure is negligible, and the geochemical system shows a favorable tendency towards self-sealing rather than degradation.
- **Control of induced effects:** The analysis rules out any significant risk of induced seismicity for the pilot phase, as the injection-induced pressures and thermal stresses remain well within the safe operating window of the reservoir-seal system. **This directly addresses a key stakeholder concern with quantitative evidence.**

Therefore, from a risk perspective, there are no outstanding technical safety objections to proceeding with the pilot injection at the Lopín site. The pilot can be authorized with a high degree of confidence in its safety, **serving as a critical validation step for the site's behavior.**

2. A defined and manageable path for industrial-scale storage

The assessment of industrial-scale scenarios confirms the site's potential for larger-scale storage, while underscoring that its realization is conditional upon active and careful risk management. The outstanding uncertainties have been clearly identified, and the pathway to resolve them—through targeted characterization and phased operational learning—is well defined**.**

- **Pressure management is paramount:** The transition to industrial-scale CO_2 injection shifts the dominant risk from plume migration to pressure buildup. Storage capacity is not limited by pore volume but by the site's ability to inject without exceeding the geomechanical limits of the containment system. Pressure evolution, hydraulic connectivity, and fault reactivity therefore form the central triad governing safe industrial-scale injection.
- **A risk-informed, adaptive strategy is essential:** A phased implementation strategy remains the "no-regrets" path forward. The pilot phase must be leveraged as a critical de-risking stage to reduce uncertainties in reservoir permeability, large-scale connectivity, and fault behavior. This learning-by-doing approach is the cornerstone of responsible scale-up and enables the definition of clear operational thresholds linking pressure, deformation, and fault stability**.**
- **Risks are mitigable and managed:** The identified risks associated with industrial-scale CO_2 storage are not prohibitive. They represent engineering challenges that can be effectively mitigated through a tailored Monitoring, Measurement, and Verification (MMV) plan, a robust Corrective Measures Plan, and targeted design adaptations where necessary. Project viability at scale depends not on the absence of challenges, but on the strength of the framework established to manage them**.**
- **Methodological refinements for industrial deployment:** This assessment demonstrates that probabilistic methods provide robust screening-level risk characterization, with conscious methodological limitations. The assumption of radial symmetry effectively identifies systemic risks but does not capture location-specific variations in fault reactivity. Similarly, while conservative friction angles ensure safety margins for screening, operational design requires the refined parameterization demonstrated in detailed geomechanical analysis. These methodological distinctions represent complementary capabilities within a comprehensive

risk management framework, where efficient probabilistic screening guides targeted deployment of resource-intensive detailed modeling

3. Synthesis: An actionable and defensible risk profile

This study moves beyond a qualitative checklist to produce **a quantitative and actionable risk profile**. By combining Monte Carlo simulations with a Bayesian Belief Network, it offers a clear and reliable understanding of how uncertainty affects system behavior. **This methodology not only quantifies risk but also supports confident and informed decision-making**.

Overall, the Lopín site emerges as a suitable location for CO_2 storage. The risk assessment for the pilot phase is positive and provides a solid foundation for obtaining the necessary permissions. Looking ahead, the framework established here offers a transparent, risk-informed roadmap for safely and responsibly scaling up operations. **The transition from pilot to industrial storage is not a leap of faith but a structured, data-driven process**. This work turns the potential of large-scale carbon storage in the Ebro Basin into a practical and controlled reality.

In conclusion, this risk assessment employs a **system reliability framework** to evidence the high level of safety associated with the pilot injection at Lopín. Furthermore, it delivers a **prioritised blueprint for risk management**, showing that the optimisation of future industrial-scale storage capacity is an exercise in characterised reservoir management and controlled pressure evolution, rather than a question of fundamental containment security.

7. References

Arche A, López-Gómez JL, Marzo M, Vargas H, 2004. The siliciclastic Permian-Triassic deposits in Central and northeastern Iberian Peninsula (Iberian, Ebro and Catalan basins): a proposal for correlation. Geologica Acta 2(4):305-320.

Arlegui L, Simón JL, 2001. Geometry and distribution of regional joint sets in a non-homogeneous stress field: case study in the Ebro basin (Spain). J Struct Geol 23:297–313.

Aven, T., & Renn, O. (2009). On risk defined as an event where the outcome is uncertain. Journal of Risk Research, 12(1), 1–11. https://doi.org/10.1080/13669870802488883

Bouquet, S. 2024. Report on static modelling with uncertainties. Deliverable D3.2. EU H2020. PilotSTRATEGY project 101022664, report, pp 275

Bratvold, Reidar B., Bickel, J. Eric, and Hans Petter Lohne. "Value of Information in the Oil and Gas Industry: Past, Present, and Future." SPE Res Eval & Eng 12 (2009): 630–638. doi: https://doi.org/10.2118/110378-PA

Callas C, Saltzer SD, Davis JS, Hashemi SS, Kovscek AR, Okoroafor ER, Wen G, Zoback MD, Benson SM, 2022. Criteria and workflow for selecting depleted hydrocarbon reservoirs for carbon storage. Applied Energy 324, 119668. https://doi.org/10.1016/j.apenergy.2022.119668

Canteli, P.; Moreno, I.; Ron, M, Le Gallo, Y., Casacão, J., Sliwinska, A., Krawczyk P., Tartaras, E., Tzimeas, C., Ktenas, D., Tyrologou, P., Karatrantou, C. & Koukouzas, N. 2025. Final concept description and preliminary consideration by regions. WP4-Deliverable D4.3, PilotSTRATEGY EU project (101022664)

Canteli, P.; Moreno, I.; Ron, M, Le Gallo, Y., Casacão, J., Sliwinska, A., Krawczyk P., Tartars, E., Ktenas, D., Tyrologou, P., Karatrantou, C. & Koukouzas, N. 2025b. Economic evaluation of alternatives and prioritization results. WP4-Deliverable D4.9, PilotSTRATEGY EU project (101022664)

Chang WK, Bryant SL, 2007. Dynamics of CO2 plumes encountering a fault in a reservoir. Presented at the 6th Annual Conference on Carbon Capture and Sequestration, Pittsburgh, Pennsylvania, May 7–11, 2007.

Chassagne, R. 2024. Report on optimization – Injection strategy and storage capacity. Deliverable D3.3. EU H2020 PilotSTRATEGY project 101022664, report, pp 170.

Chesnokov C., Rouhi Farajzadeh, Kofi Ohemeng Kyei Prempeh, Siavash Kahrobaei, Jeroen Snippe, Pavel Bedrikovetsky. Analytical model for Joule-Thomson cooling under heat exchange during CO2 storage. Advances in Water Resources, Volume 190, 2024, 104758. https://doi.org/10.1016/j.advwatres.2024.104758

Deliverable D3.4 Report on CO2 fate on the long-term (draft version) October 2025. EU H2020. PilotSTRATEGY project 101022664

Deliverable D3.5 Report on near wellbore, caprock and faults integrity (draft version) September 2025. EU H2020. PilotSTRATEGY project 101022664

Deliverable D6.4 Stakeholder engagement: regional committees (draft version) SECOND REGIONAL STAKEHOLDER COMMITTEE IN SPAIN (EBRO BASIN). 2023. EU H2020. PilotSTRATEGY project 101022664

The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

Fominykh, S.; Stankovski, S.; Markovic, V.M.; Petrovic, D.; Osmanovi´c, S. Analysis of CO2 Migration in Horizontal Saline Aquifers during Carbon Capture and Storage Process. Sustainability 2023, 15, 8912. https://doi.org/10.3390/su15118912.

GoldSim Technology Group (2025), GoldSim User's Guide (Version 15), https://www.goldsim.com/Web/Customers/Education/Documentation/.

Gomez JJ, Goy A, Barrón E, 2007. Events around the Triassic-Jurassic boundary in northern and eastern Spain. A review. Palaeogeography, Palaeoclimatology, Palaeoecology 244:89-110, https://doi.org/10.1016/j.palaeo.2006.06.025

Heidbach, O., Rajabi, M., Reiter, K., Ziegler, M. (2016): World Stress Map 2016, GFZ Data Service, doi:10.5880/WSM.2016.002.

Hesse MA, Tchelepi HA, Orr Jr FM, 2006. Scaling analysis of the migration of CO2 in saline aquifers. In: SPE Annual Technical Conference and Exhibition (SPE 102796), San Antonio, Texas, USA, 2006.

Houseworth JE, 2012. Matched Boundary Extrapolation Solutions for CO2 Well-Injection into a Saline Aquifer. Transp Porous Med 91, 813-831. https://doi.org/10.1007/s11242-011-9874-y

Hurtado, A., Eguilior, S. & Recreo, F. Methodological development of a probabilistic model for CO2 geological storage safety assessment. Int J Energy Environ Eng 5, 84 (2014). https://doi.org/10.1007/s40095-014-0084-6

IEA (2020), CCUS in Clean Energy Transitions, IEA, Paris https://www.iea.org/reports/ccus-in-clean-energy-transitions , Licence: CC BY 4.0

IGME-DGA, 2009. Memoria de la actividad 2: apoyo a la caracterización adicional de las masas de agua subterránea en riesgo de no cumplir los objetivos medioambientales en 2015. Demarcación Hidrográfica del Ebro. 2009. Proyecto: encomienda de gestión para la realización de trabajos científico-técnicos de apoyo a la sostenibilidad y protección de las aguas subterráneas. Servicio de Información Documental del IGME. Código 63809. http://info.igme.es/SidPDF/139000/918/139918_0000031.pdf

IGME-DGA, 2010. Encomienda de gestión para la realización de trabajos científico-técnicos de apoyo a la sostenibilidad y protección de las aguas subterráneas. Actividad 4: Identificación y caracterización de la interrelación que se presenta entre aguas subterráneas, cursos fluviales, descargas por manantiales, zonas húmedas y otros ecosistemas naturales de especial interés hídrico Demarcación Hidrográfica del EBRO. Servicio de Información Documental del IGME. Código 64040. http://info.igme.es/SidPDF/148000/21/148021_0000002.pdf

INE, 2023.Instututo Nacional de Estadística. Cifras oficiales de población de los municipios españoles en aplicación de la Ley de Bases del Régimen Local (Art. 17). https://www.ine.es/dynt3/inebase/es/index.htm?padre=525

Joshi A., Gangadharan S., Leonenko Y. Modeling of pressure evolution during multiple well injection of CO2 in saline aquifers. Journal of Natural Gas Science and Engineering. Volume 36, Part A, 2016, Pages 1070-1079. https://doi.org/10.1016/j.jngse.2016.06.005

The PilotSTRATEGY project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 101022664

Jurado MJ, 1990. El Triásico y Liásico basal evaporíticos del subsuelo de la cuenca del Ebro. In: Ortí, F., Salvany, J.M. (Eds.), Formaciones evaporíticas de la Cuenca del Ebro y cadenas periféricas y de la zona de Levante. Enresa, pp. 21-28.

Kumar N, 2008. CO2 sequestration: understanding the plume dynamics and estimating risk. Thesis Degree of Master of Science in Engineering, The University of Texas at Austin, May 2008.

Lanaja, J.M. Contribución de la exploración petrolífera al conocimiento de la geología de España" (IGME), 1987. Pp. 465. ISBN 978-84-7474-398-2.

Le Guénan, T. 2024 Risk assessment in the regions: Ebro, Lusitanian and Paris Basins – First round Technical note

MacMinn, C.W. and Juanes, R. Post-injection spreading and trapping of CO2 in saline aquifers: impact of the plume shape at the end of injection. Comput Geosci 13, 483–491 (2009). https://doi.org/10.1007/s10596-009-9147-9

Mathias S.A., Jon G. Gluyas, Curtis M. Oldenburg, Chin-Fu Tsang. Analytical solution for Joule–Thomson cooling during CO2 geo-sequestration in depleted oil and gas reservoirs. International Journal of Greenhouse Gas Control, Volume 4, Issue 5, 2010, Pages 806-810. https://doi.org/10.1016/j.ijggc.2010.05.008

Mathias SA, Hardisty P, Trudell M, Zimmerman R, 2009. Approximate Solutions for Pressure buildup during CO2 injection in brine aquifers. Transport in Porous Media 79:265-284. https://doi.org/10.1007/s11242-008-9316-7

Mathurin F., Carneiro, J., López-Gutiérrez, J., Matos, C., Moreno, I. and Wilkinson, M., 2023. Deliverable 2.11 – Report on the regional hydrogeology of the three study areas: Paris Basin (France), Lusitanian Basin (Portugal) and Ebro Basin (Spain). EU H2020 PilotSTRATEGY project 101022664, 147 pp.

Moreno I., J. García, J. F. Mediato, P. Fernández-Canteli, B. Benjumea, F. Rubio, C. Ayala, D. M. García, J. Martínez, C. Rey, P. Clariana, B. del Moral, E. R. Berrezueta, B. Ordóñez, E. Fernández de Arévalo, R. Soto, J. López, A. García, J. M. Llorente, M. Castillo, E. Pueyo. Date: July 2023. Deliverable 2.7 Geological Models - EBRO BASIN SPAIN. ANNEXES, July 2023. PilotSTRATEGY project

Nordbotten JM, Celia MA, 2006a. Analysis of plume extent using analytical solutions for CO2 storage. In: Proceedings of the XVI International Conference on Computational Methods in Water Resources, ed. P.J. Binning, P. Engesgaard, H. Dahle, G. Pinder, and W. Gray. Copenhagen, Denmark, June 2006. http://proceedings.cmwr-xvi.org; http://arks.princeton.edu/ark:/88435/dsp01z603qx41q

Nordbotten JM, Celia MA, 2006b. Similarity solutions for fluid injection in confined aquifers. Journal of Fluid Mechanics 561:307-327. doi:10.1017/S0022112006000802

Olaiz, A., Diez, J., Ocampo, G., Borges, J.F., Cartaxo, J., Marro, G., Pángaro, F., Ron, M., Canteli, P., Mediato, J., Moreno, I., 2024. Report on Local Seismicity for Lusitania & Ebro Basin, including Earthquake Catalog. WP2-Deliverable D2.5, EU H2020 PilotSTRATEGY project 101022664, 86 pp.

Ortí F., Salvany J.M., Rosell L., Castelltort X., Inglès M., Playà E.. Middle Triassic evaporite sedimentation in the Catalan basin: Implications for the paleogeographic evolution in the NE Iberian platform. Sedimentary Geology, Volume 374, 2018, Pages 158-178, ISSN 0037-0738. https://doi.org/10.1016/j.sedgeo.2018.07.005.

Parkhurst and Appelo, 1999. User's guide to PHREEQC. USGS

Pearl, J. (1988). Probabilistic Reasoning in Intelligent Systems. Morgan Kaufmann

Quintessa (2014). Generic CO_2 FEP Database, Version 2.0. Quintessa Limited, Henley-on-Thames, United Kingdom. Open access on-line database https://www.quintessa.org/co2fepdb/

Quirantes J, 1978. Estudio sedimentológico y estratigráfico del Terciario continental de Los Monegros. Institución Fernando El Católico (C.S.I.C.), Diputación Provincial de Zaragoza, 200 pp.

Rutqvist, J. The Geomechanics of CO2 Storage in Deep Sedimentary Formations. Geotech Geol Eng 30, 525–551 (2012). https://doi.org/10.1007/s10706-011-9491-0

Rutqvist J., Hoi-Hai Liu, Donald W. Vasco, Lehua Pan, Karl Kappler, Ernie Majer. Coupled non-isothermal, multiphase fluid flow, and geomechanical modeling of ground surface deformations and potential for induced micro-seismicity at the In Salah CO2 storage operation. Energy Procedia, Volume 4, 2011, Pages 3542-3549. https://doi.org/10.1016/j.egypro.2011.02.282.

Vilarrasa, V., Carrera, J., Olivella, S., Rutqvist, J., and Laloui, L.: Induced seismicity in geologic carbon storage, Solid Earth, 10, 871–892, https://doi.org/10.5194/se-10-871-2019, 2019.

Wilkinson, M. 2023. Deliverable 2.7 – Conceptual Geological Models of the Portugal, Spain and France. PilotSTRATEGY project, Grant Agreement: 101022664.

Zapata Y., Kristensen M.R., Huerta N., Brown C., Kabir C.S., Reza Z. CO2 geological storage: Critical insights on plume dynamics and storage efficiency during long-term injection and post-injection periods. Journal of Natural Gas Science and Engineering, Volume 83, 2020, 103542. https://doi.org/10.1016/j.jngse.2020.103542

8. APPENDIX

8.1 Risk Identification Update and Scenario Assessment

The systematic identification and definition of risk scenarios for the Lopín site was conducted using a structured methodology for safety assessment of geological disposal, drawing on the expertise of Quintessa in system definition and scenario development (Quintessa, 2014; Le Guénan, 2024). This approach is centered on a comprehensive FEP (Features, Events, and Processes) analysis, which provides a structured framework for identifying all potentially relevant scenarios that could affect the storage system's long-term performance and safety.

The initial FEP-based screening was updated through collaborative workshops, resulting in a refined list of safety scenarios for detailed assessment in Phase 2. The following sections describe each relevant scenario conceptually—as derived from the systematic FEP analysis—and summarize the assessment approach and key findings. Schematic diagrams illustrating the main causes and potential consequences for each primary scenario are provided in Appendix 8.2.

8.1.1 Evolution Scenarios

Leakage from an Operating Well

- Scenario Description: Loss of containment through the injection well or its components due to material failure, corrosion, or improper completion.
- Assessment Approach & Rationale: Qualitative analysis conducted in coordination with WP4. The assessment assumes that all necessary safety measures—including robust well design, corrosion-resistant materials, and continuous integrity monitoring—will be implemented as standard practice, reducing this risk to a very low level.

Leakage from an Abandoned Well

- Scenario Description: CO_2 migration to the surface through a pre-existing, improperly sealed wellbore that intersects the CO_2 plume.
- Assessment Approach & Rationale: Quantitative probabilistic assessment. The nearest known well (Lopín-1) is ~10 km from the injection point. Monte Carlo simulations of plume extent, both during injection and over a 1,000-year post-injection period, confirm a negligible probability of the plume reaching this or any other well.

Leakage through Seal Formation

- Scenario Description: Vertical migration of CO_2 through the primary caprock (Buntsandstein B2/Rané formation) via two mechanisms: mechanical fracturing from injection-induced overpressure or through inherent, undetected high-permeability pathways.
- Assessment Approach & Rationale: Semi-quantitative assessment. Geomechanical analysis compared the probabilistically modeled pressure increase against the formation's fracture pressure. Geochemical modeling (PHREEQC) assessed the long-term integrity of the seal, indicating chemical stability and a potential for "self-sealing." The presence of a highly competent secondary regional seal (Keuper formation) provides a further robust barrier.

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Leakage via Existing Faults

- Scenario Description: CO_2 using fault zones as preferential conduits for upward migration. The site contains two relevant fault systems: nearby NW-SE normal faults (~400 m from injection) and more distant NNE-SSW reverse faults (>6 km).
- Assessment Approach & Rationale: Semi-quantitative assessment. The probability of the plume reaching the nearest normal faults was quantitatively evaluated. Subsequent migration beyond the secondary containment system (Muschelkalk M1/M3) was assessed conceptually, concluding that faults do not provide a credible pathway to the surface or overlying aquifers.

Exceeded Lateral Extent (CO_2)

- Scenario Description: The CO_2 plume migrates laterally beyond the predicted boundaries of the storage complex, potentially reaching unidentified leakage pathways or conflicting with other subsurface resources.
- Assessment Approach & Rationale: Qualitative assessment. This scenario is considered highly unlikely due to the site's structural closure (horst configuration) and the presence of bounding faults that act as lateral seals. The extensive, competent regional seal (Keuper) further ensures containment.

Structural Spill

- Scenario Description: CO_2 migrates beyond the spill point of the structural trap, typically due to underestimation of the storage capacity or overfilling of the structure.
- Assessment Approach & Rationale: Qualitative assessment. Ruled out based on the conservative storage capacity estimates and the implementation of a phased injection strategy with active pressure monitoring, which will prevent overfilling.

Migration of Formation Brine

- Scenario Description: Injection-induced pressure increase displaces native brines from the storage formation, potentially impacting adjacent aquifers or other subsurface resources.
- Assessment Approach & Rationale: Qualitative assessment. Considered non-credible due to the site's hydrogeological isolation, the lack of hydraulic connectivity with freshwater aquifers, and the immense dilution capacity in the deep subsurface. No conflicts with other land uses are foreseen.

CO_2 Accumulation in a Secondary Reservoir

- Scenario Description: CO_2 that has leaked through the primary seal becomes trapped in a shallower geological formation (e.g., Muschelkalk M1 or M3).
- Assessment Approach & Rationale: Semi-quantitative assessment. This scenario is intrinsically linked to and evaluated as a potential consequence of leakage through the primary seal or faults. The secondary containment system is considered part of the overall storage complex.

Uplift or Subsidence of Ground

- Scenario Description: Injection-related pressure changes cause deformation of the reservoir and overburden, leading to measurable surface displacement.

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- Assessment Approach & Rationale: Qualitative assessment. Deemed negligible due to the depth of the reservoir, the relatively small injection pressures, and the ability of the overlying, plastic clay-rich and evaporitic sequences to absorb strain without transmitting it to the surface.

Unforeseen CO_2 Impacts

- Scenario Description: Unexpected and unanticipated interactions between the stored CO_2 and the geological system or the environment.
- Assessment Approach & Rationale: Qualitative assessment. The systematic FEP (Features, Events, and Processes) analysis conducted as part of the risk identification process makes this scenario highly improbable. The site's characteristics (low population, no nearby industries, absence of sensitive receptors) further reduce potential consequences.

8.1.2 Perturbative Scenarios

Induced Seismicity

- Scenario Description: The injection of CO_2, through increased pore pressure and thermal stress, reactivates pre-existing fractures or faults, potentially causing micro-seismicity or, in a worst case, a felt seismic event.
- Assessment Approach & Rationale: Semi-quantitative assessment. A geomechanical analysis was conducted to calculate the probability of exceeding the critical pressure for fault reactivation, integrating both pressure and thermal stress effects from WP3 modeling results.

Natural Seismicity

- Scenario Description: A natural seismic event causes loss of mechanical integrity in the reservoir, seal, or wellbores.
- Assessment Approach & Rationale: Scenario dismissed from detailed analysis. The Lopín area exhibits very low seismic activity, with a historical record of only 15 minor events since 1900 (max magnitude 2.6). The regional maximum magnitude (4.1) at a significant distance (30 km) poses a negligible threat to storage integrity.

Disruption by a Later Activity

- Scenario Description: Future human activities (e.g., drilling for geothermal energy, mining) unintentionally penetrate the storage complex and compromise its integrity.
- Assessment Approach & Rationale: Qualitative assessment. This scenario is considered non-credible as there are no known economically viable geological resources (geothermal, mineral) in the area that would motivate such future activity at these depths.

Flow Modifications

- Scenario Description: CO_2 injection alters the natural groundwater flow patterns within the storage formation or in overlying/underlying aquifers.
- Assessment Approach & Rationale: Qualitative assessment. For the pilot-scale injection, the volume and pressure changes are too small to cause significant regional flow alterations. Available data also indicates that the natural groundwater flow in the deep Buntsandstein aquifer is extremely slow or stagnant.

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8.1.3 Performance Scenarios

Injectivity Loss

- Scenario Description: A reduction in the ability to inject CO_2 at the desired rate, due to near-wellbore formation damage, chemical precipitation, or mechanical issues.
- Assessment Approach & Rationale: Qualitative assessment. This is primarily an operational risk to be managed by WP4 through well design, water compatibility studies, and operational controls. It has low safety consequences.

Smaller Capacity than Expected

- Scenario Description: The effective storage volume of the site is less than initially estimated, potentially limiting the project's long-term viability.
- Assessment Approach & Rationale: Qualitative assessment. Addressed through conservative capacity estimates and the phased injection strategy, which will use the pilot phase to calibrate and validate the storage model.

Reservoir Pressurization due to Unexpected Compartmentalization

- Scenario Description: The storage formation is divided into isolated compartments by previously undetected sealing faults, leading to higher-than-expected pressure buildup in the injection compartment.
- Assessment Approach & Rationale: Qualitative assessment. This is a key uncertainty managed by the adaptive risk strategy. The pilot injection and subsequent monitoring will be used to detect and characterize potential compartmentalization.

Accidental Over-filling

- Scenario Description: Injection of more CO_2 than the storage complex can safely contain, leading to a loss of containment.
- Assessment Approach & Rationale: Qualitative assessment. Ruled out by design through the implementation of a rigorous Monitoring and Verification (MMV) plan and a pre-defined pressure management strategy that will halt injection before reaching safety limits.

Unexpected Variations in CO_2 Composition

- Scenario Description: Impurities in the injected CO_2 stream (e.g., SO_x, NO_x, O_2) lead to unexpected geochemical reactions that alter the reservoir or wellbore integrity.
- Assessment Approach & Rationale: Qualitative assessment. This is an operational input parameter controlled at the capture facility. The risk is managed through source stream monitoring and specification agreements, and is considered outside the scope of this geological assessment.

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8.2 Scenario Diagrams: Causes and Consequences

EVOLUTION SCENARIOS

Potential causes	**Main event (Scenario)**	**Consequences**
Well blow-outs during well interventions	**Leakage from operating well**	Elevated concentration of CO_2 in the atmosphere
Leakage through well loss of integrity		Elevated concentration of CO_2 (and ^{222}Rn, CH_4 and/or H_2S) in the groundwater
Inadequate wellbore construction, comprising the design, lining, drilling and/or completion of the well		Less CO_2 stored / lower injection rate
Failure of one or more well barrier elements		Major maintenance works on the well or plugging the well
Overpressure near wellbore		Potential for temporary asphyxiant cloud accumulation in low areas (dependent on prevailing wind conditions and CO_2 concentrations) if not dispersed

Threat Response

Ensure well integrity through robust design, construction, and regular integrity testing.
Implement emergency response and blowout contingency plans.
Add backup injector well.
External audit

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EVOLUTION SCENARIOS

Potential causes	Main event (Scenario)	Consequences
No barrier installed over the storage zone to be pressurized (well remediation)	**Leakage from legacy abandoned well**	Elevated concentration of CO_2 in the atmosphere
Inadequate wellbore construction, comprising the design, lining, drilling and/or completion of the well, and abandonment		Less CO_2 stored / lower injection rate
Failure of one or more well barrier elements		Major maintenance works on the well or plugging the well
Absence or inadequacy of well-pluggings		
No legacy well inventory available		

Threat Response

Conduct legacy well inventory and integrity assessment.
Apply plug verification and re-abandonment if necessary.
Engage regulators and prepare contingency plans.
Implement a site-specific MMV program and continuous monitoring for legacy wells affection.
Plume and pressure front dynamic modeling for legacy wells affection.

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EVOLUTION SCENARIOS

Potential causes	Main event (Scenario)	Consequences
Due to the presence of an undetected high permeability zone	Leakage through seal formation	Elevated concentration of CO_2 in the atmosphere
Discontinuities (fractures, faults) not detected in the caprock		Elevated concentration of CO_2 (and ^{222}Rn, CH_4 and/or H_2S) in the groundwater of Jurassic/Cenozoic aquifer
Geochemical degradation of caprock		Less CO_2 stored
Caprock thin or discontinuous		Create lateral and/or vertical pathways for CO_2 migration
		Migration to shallow aquifers, causing the possible salinization of freshwater resources

Threat Response

Implement a site-specific MMV program and continuous monitoring of caprock integrity.
Use seismic and geochemical tools to detect anomalies.
Apply ALARP principles to ensure risk is reduced to acceptable levels.
Perform historical well data review and integrity risk analysis.
MMV baseline characterization

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EVOLUTION SCENARIOS

Potential causes	**Main event (Scenario)**	**Consequences**
Via open faults and/or fractures reached by the CO_2 plume	**Leakage along faults or fractures**	Elevated concentration of CO_2 in the atmosphere
Not observed/interpreted faults from seismic data		Elevated concentration of CO_2 (and ^{222}Rn, CH_4 and/or H_2S) in the groundwater or atmosphere
Heterogeneities can result in directional variations in permeability (fluids mobility)		Less CO_2 stored
Potential fractures/fault physical or chemical reactivation (due to the arrival of CO_2 inside the fractures)		CO_2 accumulation in a secondary reservoir
		Fluid migration

Threat Response

Conduct geomechanical modeling to assess fault reactivation potential.
Use high-resolution seismic surveys and pressure monitoring to track plume migration.
Establish fault avoidance zones and adjust injection strategy accordingly.
Use NRAP-STSF tool for short-term seismic forecasting

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EVOLUTION SCENARIOS

Potential causes	Main event (Scenario)	Consequences
Movement of CO_2 outside the lateral boundary	Lateral leakage	Elevated concentration of CO_2 in the atmosphere
Interaction with other resources		Elevated concentration of CO_2 (and ^{222}Rn, CH_4 and/or H_2S) in the groundwater
CO_2 plume has reached the existing faults of the storage complex due to the processes related to the transport of CO_2 in formation water		Less CO_2 stored
High CO_2 volumes injected		Faults reactivation or lateral leakage
Non-expected leakage paths associated with uncertainties in the geological/reservoir model		Contaminate near-surface aquifers, contamination of potable water supplies
Displacement of saline formation fluids		Storage redimensioning
Uncertainty in the background water flow velocity		Regulatory and legal problems: Violation of environmental or subsoil use permits

Threat Response

Characterize lateral seals and up-dip facies.
Monitor plume migration using geophysical tools.
Apply containment modeling and adjust injection strategy to avoid lateral migration.
Build static model and run dynamic simulations.
Continuous MMV program and lateral seal verification

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EVOLUTION SCENARIOS

Potential causes

- Exceeding expected lateral extent
- Reservoir is overfilled
- High CO_2 volumes injected
- Uncertainty in the background water flow velocity
- Uncertainty in reservoir characterization

Main event (Scenario)

Structural spill

Consequences

- Unexpected CO_2 migration. High concentration of CO_2 in the atmosphere
- Elevated concentration of CO_2 (and ^{222}Rn, CH_4 and/or H_2S) in the groundwater
- Less CO_2 stored
- Interaction with other resources
- Displacement of saline formation fluids. Contaminate aquifers
- Redimensioning of the storage area and/or the CO_2 plume dispersion
- Regulatory and legal problems: Violation of environmental or subsoil use permits

Threat Response

Design injection volumes and rates to remain below spill point thresholds.
Implement real-time reservoir pressure monitoring and dynamic modeling to anticipate plume behavior.
Fit-for-purpose data acquisition campaign

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EVOLUTION SCENARIOS

Potential causes

- Increased displacement of high salinity water formation
- Pressure wave created by CO_2 injection travels much further than the physical CO_2 front, therefore causing the displacement of saline formation fluids
- Existence of high-conductivity pathways
- Insufficient geological modelling or characterisation

Main event (Scenario)

Migration of formation brine outside expected boundaries

Consequences

- Interaction with other resources
- Migration to shallow aquifers, causing the possible salinization of freshwater resources
- Regulatory and legal problems: Violation of environmental or subsoil use permits
- Additional monitoring or mitigation costs

Threat Response

Model pressure front propagation and brine displacement.
Monitor salinity in shallow aquifers.
Adjust injection strategy to minimize pressure wave impact.
Characterization of hydraulic unit (baseline).
Implement a site-specific MMV program and continuous monitoring for aquifers.

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EVOLUTION SCENARIOS

Potential causes	Main event (Scenario)	Consequences
Mass injected and pressure increment progressively change ground level	**Uplift or subsidence of ground**	Damage to third parties installations
In the long term, if CO_2 causes rearrangement or collapse of pores		Alteration of hydrological systems
Differential ground motions associated with faults or structural discontinuities		

Threat Response

Monitor surface deformation using InSAR and GPS.
Conduct geomechanical modeling to predict ground movement.
Engage with local infrastructure stakeholders.
InSAR baseline.

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EVOLUTION SCENARIOS

Potential causes	Main event (Scenario)	Consequences
Incomplete baseline environmental studies	**Unforeseen CO2 impacts**	Regulatory intervention
Unexpected interactions between injected CO_2 and subsurface ecosystems		Need for additional mitigation measures
Cumulative impacts with other projects		Reputational harm
		Project suspension
		Potential CO_2 concentrationin confined areas with safety consequences

Threat Response

Conduct comprehensive baseline environmental studies.
Implement adaptive MMV programs to detect and respond to unexpected impacts.
Engage with environmental regulators early.
Environmental risk register and early warning systems.

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PERTURBATIVE SCENARIOS

Potential causes	Main event (Scenario)	Consequences
Natural regional stress regime	**Natural seismicity**	Perceptible earthquakes
		CO_2 leakages. Elevated concentration of CO_2 (and ^{222}Rn, CH_4 and/or H_2S) in the groundwater or surface
		Loss of containment of a well
		Mechanical changes of the reservoir/caprock
		New faults may appear or existing faults may reactivate
		Modification of the physical properties of rocks (porosity, permeability)
		Social opinion blaming the project as causing the earthquake
		Need of legal demonstration that earthquake was not induced by CO_2 injection

Threat Response

Establish baseline seismicity data and monitor continuously.
Differentiate between natural and induced events using geophysical analysis. Communicate findings transparently to stakeholders.
Natural hazard mapping and MMV integration.

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PERTURBATIVE SCENARIOS

Potential causes	Main event (Scenario)	Consequences
Loss of mechanical integrity in the reservoir, leading induced seismicity on other subsurface structures	**Induced seismicity**	Perceptible earthquakes
Over-pressurisation		Loss of containment of a well
Reach of the temperature front to fractures		Mechanical changes of the reservoir/caprock
Migration of CO_2 or brine to seismically sensitive areas (CO_2 intrusion into faults - Interaction of CO_2 with the fault filler,...)		Damage to third parties infrastructures
Simultaneous extraction of saline water causing pressure heterogenities in the area		New faults may appear or existing faults may reactivate
		Modification of the physical properties of rocks (porosity, permeability)
		Abnormal increasing of seismic events occurrence in a given area than those retrieved from the historical seismicity chart

Threat Response

Apply Traffic Light Protocol (TLP) and monitor seismicity.
Use geomechanical modeling and adjust injection rates.
Engage with local authorities for risk communication.
Seismic baseline characterization and MMV.

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PERTURBATIVE SCENARIOS

Potential causes	Main event (Scenario)	Consequences
Different administrative control of the CO_2 storage complex after closure of the project (inadvertent actions)	**Disruption by a later activity**	Elevated concentration of CO_2 in the atmosphere
Development of new infrastructure close to the storage complex		Elevated concentration of CO_2 (and ^{222}Rn, CH_4 and/or H_2S) in the groundwater
Drilling new wells		Loss of containment of a well
Potentially exploitable natural resources		Modification of the physical properties of rocks (porosity, permeability)

Threat Response

Establish long-term land use agreements and buffer zones around the storage site
Monitor nearby developments and coordinate with local planning authorities to prevent interference.
Stakeholder mapping and land use coordination.
Administrative review and zoning control.

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PERTURBATIVE SCENARIOS

Potential causes	Main event (Scenario)	Consequences
High CO_2 injection rates	**Changes in groundwater flow, within the reservoir or in other layers of the storage complex**	Modified hydrology and hydrogeology
Dissolution and/or precipitation of minerals due to the injection of CO_2, since the CO_2 reacts with the host rock		Elevated concentration of CO_2 (and ^{222}Rn, CH_4 and/or H_2S) in the groundwater
Existence of high-conductivity pathways		Storage redimensioning
Mechanical changes of the reservoir/caprock		Halt of injection temporary
		Aquifer affected with brine

Threat Response

Conduct hydrogeological modeling to assess flow changes.
Monitor aquifer chemistry and pressure.
Adjust injection strategy to minimize hydrological impacts.
Baseline hydrogeological survey and MMV.

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PERFORMANCE SCENARIOS

Potential causes	**Main event (Scenario)**	**Consequences**
Reduced porosity due to chemical precipitation	**Loss of injectivity**	Less CO_2 stored, lower injection rates, insuficient for project objectives
Physical pore obstruction		Wells will require more frequent intervention
Clay swelling		Additional wells required
Borehole deformation		Overpressurization of reservoir
Geological heterogeneities		
Insufficient geological modelling or characterisation		
Initial injectivity lower than expected		

Threat Response

Implement injectivity testing and real-time monitoring.
Use chemical inhibitors and adjust injection parameters to prevent clogging.
Design wells for flexibility in flow rates.
Use of anti-scaling agents.
Use of acid for improving rock permeability.

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PERFORMANCE SCENARIOS

Potential causes	Main event (Scenario)	Consequences
Porosity/permeability reduction due to chemical precipitation	Lower than expected capacity	Less CO_2 stored, lower injection rates, insuficient for project objectives
Lack of knowledge on coefficients reducing storage capacity from theorical to effective or interplay between various trapping mechanismns in aquifers		Modification of the geometry of the storage reservoir
Clay swelling		Wells will require more frequent intervention
Geological heterogeneities		Modification of project concept
Undetected local permeability heterogeneities		
Uncertainties in rock/fluid compositions present at reservoir conditions		
Uncertainties in reservoir geometry and properties		

Threat Response

Refine reservoir characterization using dynamic modeling.
Reassess trapping mechanisms and adjust project scope.
Consider phased expansion or alternate sites.
Update static model and re-evaluate capacity.
Capacity reassessment and contingency planning.
Conduct high-resolution seismic and stratigraphic analysis.

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PERFORMANCE SCENARIOS

Potential causes	Main event (Scenario)	Consequences
The existence of geological heterogeneities (structural and/or stratigraphic) that are either uncharacterised or undetected	**Unexpected compartmentalization**	Less CO_2 stored
Permeability heterogeneity		Reduction of the estimated capacity
		Different injection strategy
		Storage redimensioning
		Early abandonment
		Induced seismicity
		Reservoir overpressurization

Threat Response

Conduct high-resolution seismic and stratigraphic analysis.
Use tracer tests to identify flow barriers.
Compartmentalization modeling and optimize injection strategy.
Monitor pressure wave front.

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PERFORMANCE SCENARIOS

Potential causes	Main event (Scenario)	Consequences
More CO_2 injected than planned	**Accidental over-fill**	Elevated concentration of CO_2 in the atmosphere
Reservoir storage capacity is smaller than calculated		Elevated concentration of CO_2 (and ^{222}Rn, CH_4 and/or H_2S) in the groundwater
Existence of more highly permeable conduits than initially recognized		Increased pressure of the reservoir, possibly affecting the caprock and inducing seismicity
		Lateral extent of the CO_2 plume may be increased compared to that initially expected

Threat Response

Implement injection volume tracking and reservoir pressure monitoring.
Use predictive modeling to avoid exceeding capacity.
Establish emergency shutdown protocols.
Real-time injection monitoring and alarms.
Injection control and emergency planning.

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PERFORMANCE SCENARIOS

Potential causes	Main event (Scenario)	Consequences
Differences in capture technologies or industrial sources	**Unexpected variations in CO_2 composition**	Corrosion
Defficient composition monitoring		Reduced injectivity
Supply contraccts not properly defined or specified		Need for additional treatment or monitoring
		Temporary halts

Threat Response

Implement continuous monitoring of CO_2 stream composition.
Design injection and transport systems to accommodate variability.
Include purification or conditioning units if needed.
Inline composition sensors and flexible design.
Prepare contingency protocols to protect integrity and mitigate damage.
Supply contracts comprehensively detailed for CO_2 composition thresholds.

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8.3 Risk assessment appendix

8.3.1 Consistency Between Detailed Modelling (WP3) and Probabilistic Approaches (WP5).

This appendix validates the integrated modelling strategy employed throughout the project by comparing the results from the detailed numerical simulations of Work Package 3 (WP3) with the probabilistic framework of Work Package 5 (WP5). This strategy was deliberately sequential: the probabilistic models were deployed from the outset to guide decision-making under significant uncertainty. Their outputs were sequentially used to populate a dynamic Bayesian Belief Network (BBN), creating a living risk model that evolved with the project. This integrated system identified key parameters, quantified risks, and informed the strategy for data acquisition before major characterization investments were committed. The subsequent high-fidelity deterministic modelling in WP3 served to refine these predictions once improved site data was available, with its results also feeding back into the BBN. This comparison is therefore not merely a technical check, but a critical validation of the entire early-stage, adaptive risk assessment methodology. It confirms that the probabilistic approach provides a reliable and efficient foundation for the decision-support tools essential for managing complex storage projects, justifying its use in the crucial early phases where data is limited but robust decisions are required.

8.3.1.1 Methodology for Comparison

The WP5 methodology employs analytical and semi-analytical models within a Monte Carlo framework. This approach is a fundamentally different and powerful technique designed to efficiently propagate the full range of parameter uncertainties (e.g., porosity, permeability) through the system by running hundreds of thousands of simulations. For this comparison, the injection rate values from the P10, P50 and P90 scenarios defined in the high-fidelity WP3 numerical models were used as direct inputs to the WP5 probabilistic framework. This allowed for a direct comparison of outcomes based on identical operational constraints, providing a robust validation.

8.3.1.2 Comparison of CO_2 Plume Extent

The results for plume evolution show a high level of consistency between the analytical/probabilistic models of WP5 (Figure 37) and the high-fidelity numerical simulations of WP3 (Table 23)

*Table 23: WP3 CO_2 plume extent. (**Deliverable 3.4.** Report on CO_2 fate on the long-term)*

RESULTS WP3 - Deliverable 3.4. Report on CO2 fate on the long-term	CO_2 PLUME EXTENSION 30yr	CO_2 PLUME EXTENSION 1000yr
Scenario 1 (CCS-1 injector)	1.5 km - 1.7km	1.6 km - 2.35 km
Scenario 2 (LOC-D injector)		2.3 km up to 2.9 km
Scenario 3 (CCS-1 + LOC-D)	Similar (scenarios for each well)	Similar (scenarios for each well)

The WP5 probabilistic results for the post-injection period (Figure 37b) yield a maximum plume extent with a 95% confidence of approximately 2.5 km for a single well, which aligns perfectly with the upper bound of the WP3 forecast (2.35 km). This agreement validates the use of the analytical models for predicting the potential maximum reach of the CO_2 plume, a critical parameter for assessing the risk of interaction with distant faults or wells

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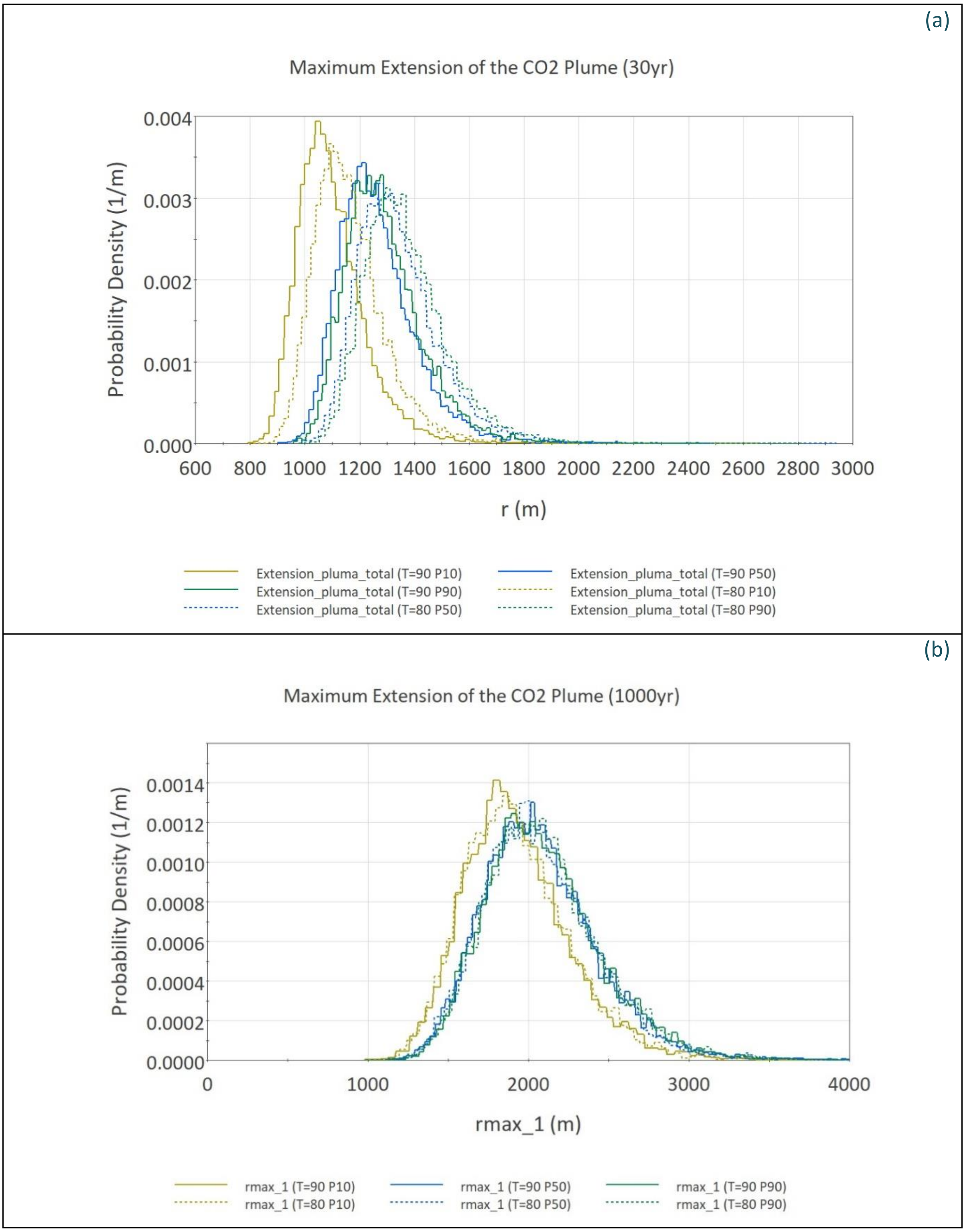

Figure 37: WP5-Modelization Result; a) injection period (30yr), b) post-inyection period (1000yr)

A critical distinction must be made between the theoretical geological capacity of the storage complex and the operationally achievable storage volume. The former is a static property of the rock volume

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and porosity, while the latter is dynamically constrained by injectivity, pressure management, and regulatory limits. This comparison focuses exclusively on the latter – the mass of CO_2 that can be injected under specific operational scenarios.

The pressure evolution and resulting injectable mass calculated by both methodologies are consistent, providing high confidence in the project's operational predictions (Table 24and Table 25).

Table 24: Injection Scenario for 1 Well (CCS-1, max BHP 285 bar) - WP3 vs WP5.

	Maximum Storage (Mton)	Optimal Rate (MTPA)	**WP5- GOLDSIM (Mton)**
P10	6.12	0.204	6.12
P50	7.62	0.254	7.62
P90	8.45	0.282	8.46

Table 25: Injection Scenario for 2 Wells (max BHP 285/292 bar) - WP3 vs WP5

	Maximum Storage (Mton)	CCS-1 Optimal Rate (MTPA)	LOC-D Optimal Rate (MTPA)	**WP5- GOLDSIM (Mton)**
P10	11.17	0.189	0.184	11,19
P50	14.90	0.227	0.269	14,88
P90	15.51	0.254	0.263	15,52

8.3.1.3 Probabilistic Validation of WP3 Injection Limits

The core of this comparison lies in the probabilistic validation of the maximum allowable injection rates derived from the detailed WP3 models. The WP3 simulations established these "limit rates" – higher for the P90 (high-permeability) case and lower for the P10 (low-permeability) case – as the maximum that would not exceed the defined Bottom Hole Pressure (BHP) limit of 285 bar.

The WP5 probabilistic analysis used these WP3-derived rates as inputs. Crucially, instead of using segregated permeability percentiles, the WP5 model applied the full permeability Probability Density Function (PDF) to each injection scenario. The results, expressed as Complementary Cumulative Distribution Functions (CCDF) for the maximum pressure increase (Figure 38 and Figure 39), validate the WP3 assumptions. They show that the probability of the pressure increase exceeding the 285 bar limit is between 5% (for the lower P10 rate) and below 20% (for the higher P90 rate) in the single-well case, with similar values for the two-well configuration.

This demonstrates that the injection rates defined by WP3 as the "limit" consistently lie in the upper tail of the pressure distribution predicted by the full range of geological uncertainty in WP5. This independent, probabilistic check confirms that the proposed operational rates are robust and have a low probability of exceeding the safe pressure window, thereby providing a strong, cross-validated basis for the injection strategy

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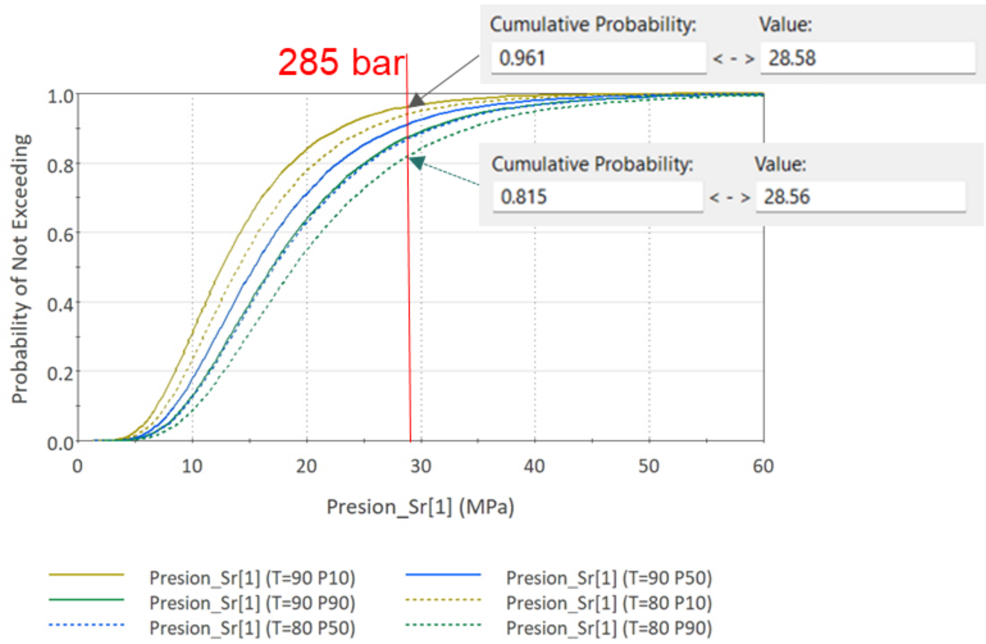

Figure 38: CCDF maximum pressure 1 well, injection rates from WP3.

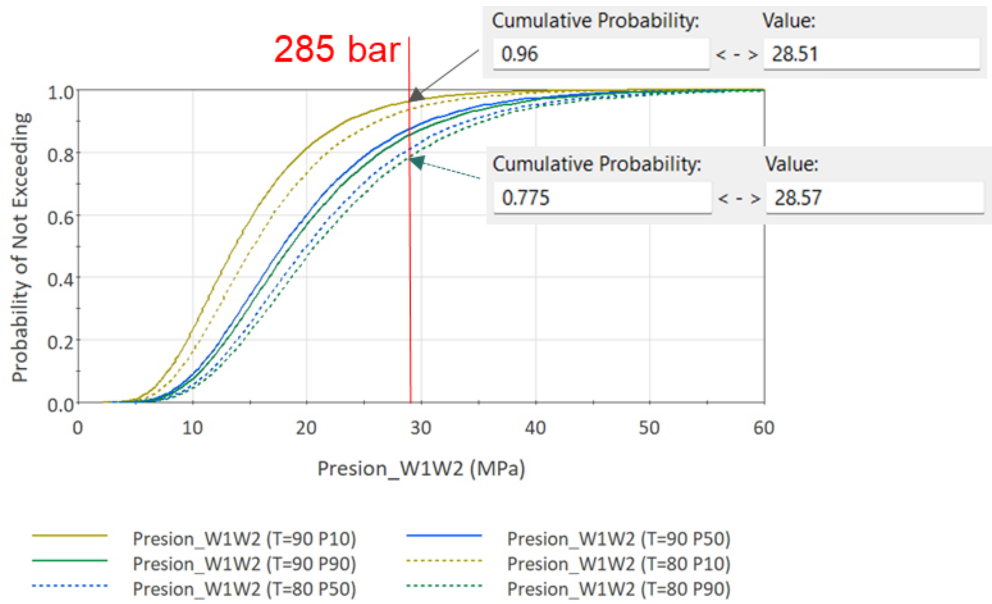

Figure 39: CCDF maximum pressure 2 wells, injection rates from WP3.

8.3.1.4 Synthesis and Conclusions

The comparison between the WP3 and WP5 modelling approaches yields the following key conclusions:

- Strong Agreement: Both detailed (WP3) and probabilistic (WP5) simulations show excellent agreement in predicting CO_2 plume extent and, most notably, total storage capacity.

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- Handling of Uncertainty: The probabilistic models successfully account for the best fit of porosity and permeability data across all WP3 cases (P10, P50, P90). The differences in WP5 results for these cases are driven solely by the variations in injection rates provided by WP3, demonstrating a coherent integration of workflows.
- Validation of Approach: The consistency validates the probabilistic methodology employed in WP5. It confirms that this efficient approach is capable of capturing the system's key behaviours and uncertainties, providing a robust basis for the risk assessment and strategic decision-making outlined in this deliverable

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