PilotSTRATEGY

WP4 -Deliverable 4.12

Pre-FEED and Final proposal for a concept development by regions

Release Status: Public

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Date: 27/04/2026

Filename and Version: PilotSTRATEGY_WP4_D4_12_ Pre-FEED and Final proposal for a concept development by regions_2026.04.25
Project ID Number: 101022664
PilotSTRATEGY (H2020- Topic LC-SC3-NZE-6-2020 - RIA)

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1. Document History

1.1 Location

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1.2 Revision History

This document has been through the following revisions:

Version No.	Revision Date	Filename/Location stored:	Brief Summary of Changes

1.3 Authorisation

This document requires the following approvals:

AUTHORISATION	Name	Signature	Date
WP Leader	Paula Canteli	PC	27/04/2026
Project Coordinator	Isaline Gravaud	IG	27/04/2026

1.4 Distribution

This document has been distributed to:

Name	Title	Version Issued	Date of Issue
Public			27/04/2026

Le Gallo, Y., Londe, L., Réveillère, A., Krawczyk, P., Śliwińska, A., Koukouzas, N., Tyrologou, P., Karatrantou, C., Carneiro, J., Canteli, P., Ron, M., Lanchan, L., Oltra, C., 2026. Pre-FEED and Final proposal for a concept development by regions. WP4-Deliverable D4.12, PilotSTRATEGY EU project (101022664)

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2. Executive summary

The PilotSTRATEGY project is investigating geological CO_2 storage sites in industrial regions of Southern and Eastern Europe to support development of large-scale carbon capture and storage (CCS). Research is focused on deep saline aquifers (DSA), which promise a large capacity for storing CO_2 captured from clusters of industry. This report is the final report from WP4 *"Pilot development and implementation plans",* which aimed at developing the pilot concepts in the 5 regions studied. Targeted to potential project developers, this report summarises the strategic information of each studied site for a documented decision about a possible implementation of a pilot based on the described development concept and its technical, economic, social, regulatory and environmental features.

Based on the WP4 previous reports, each region has defined (elements, activities, and schedule) selected scenarios, reviewed them, and carried out a techno-economic evaluation with the goal of comparing region alternatives and selecting the optimum development scenario for Paris Basin, Lusitania Basin, and Ebro Basin; and, with fewer details but following the same approach, for Silesia Basin and Macedonia Basin. The optimum developments were built and evaluated in detail by each region team as a basis for this final investment decision report.

Every region developed and evaluated their region scenarios framed by its own objectives, using a fit for purpose approach: while the French team was focused on a pilot (pre-commercial) development, the Portuguese and Spanish teams have considered, in addition, a possible commercial development. Polish and Greek cases show a more general study for the full-life case. Therefore, the different regions development and timeframe are diverse from the very beginning, providing examples at various maturity stages for possible applications in the future.

This report summarises strategic information for a proper next step decision about a possible implementation of a pilot based on the described for each region optimum development concept and its technical, economic, social and environmental features.

Paris Basin (France):

This study assesses the feasibility of a 100 kilotonne CO_2 pilot injection into the Dogger (Oolithe Blanche) saline aquifer of the Paris Basin as a preparatory step toward commercial scale carbon storage. Two CO_2 supply options—local capture from a nearby fertilizer plant or external delivery by rail—and two well configurations, onsite and offsite, are evaluated with minimal additional pipeline requirements. Environmental and social assessments identify no prohibitive constraints, with injections occurring far below freshwater aquifers and protected by a 120-meter thick Callovo Oxfordian caprock. Geological and dynamic modelling confirm adequate injectivity, limited plume migration (<350 meters laterally), and pressure dissipation within eight months, with long-term storage dominated by solubility and residual trapping. Risk analyses show no significant hazards from legacy wells or interactions with other subsurface uses. Economic results highlight CO_2 conditioning, well deviation, and monitoring as the main cost drivers, supporting the viability of future hypothetical commercial scale storage in the Paris Basin.

Lusitania Basin (Portugal):

The Portuguese CO_2 storage pilot in the northern Lusitanian Basin aims to establish the country's first operational experience with geological carbon storage and to support long-term decarbonisation objectives under the 2045 carbon neutrality target. The project plans to inject up to 100 kilotonne of

CO_2 into Lower Cretaceous sandstone reservoirs offshore Figueira da Foz, using a modular logistics chain based on rail and ship transport to avoid permanent infrastructure. The pilot will validate injectivity, pressure behaviour, plume evolution and containment, supported by an extensive MMV programme integrating seismic, downhole, environmental and integrity monitoring. Results will inform regulatory development, derisk largescale deployment and build capacity for future CCS infrastructure. Economic assessment indicates a most likely investment of €98 million, with major cost drivers related to offshore drilling, subsea systems and seismic acquisition. Environmentally, the offshore setting limits social impacts, with manageable ecological risks subject to appropriate monitoring and mitigation.

Ebro Basin (Spain):

The CO_2 storage project in the Ebro Basin proposes the full live cycle analysis of an onshore structure at 1700 meters depth including exploration phase, a 3-year injection pilot (or pre-commercial phase), and a commercial development phase. The area is low populated, no agriculture or farming developments, and close to energy and transport infrastructures. The analysis is focus on storage phase, being CO_2 capture and CO_2 transport outside of this work. Assuming a geological success, a pilot development is defined by injection of 100 kilotonne of CO_2 over approximately 3 years through a single well followed by a storage commercial development operating until estimated capacity is reached and the site is abandoned. Ebro basin proposal is evaluated techno-economically by deterministic and probabilistically approach, including a probability of geological success (Pg) and a probability of pilot success (Pp) linked to pilot injection. The results show the estimated capacity as the main driver for positive results, and the high impact of the geological uncertainties (Pg, Pp). However, a very positive economic result for the commercial case can be expected on the hight side of the total capacity, supported also for social and environmental frame, inviting to consider Lopin case for a possible future development.

Upper Silesia Basin (Poland):

This study evaluates the technical, regulatory, and economic feasibility of developing an onshore CO_2 storage project in the Upper Silesia Basin, focused on the Pągów-Milanów site. The concept follows a phased approach, beginning with a pilot injection of 30 kilotonne per year for three years using road transport, followed by a commercial phase of 300 kilotonne per year over 25 years supplied via pipeline. The selected Jurassic saline aquifer offers an estimated 31 Milliontonne storage capacity, well above the planned cumulative injection of 7.5 Milliontonne. Regulatory conditions in Poland provide a clear legal framework but involve multi-stage permitting and significant pre-investment risk. Economic analysis indicates that the pilot phase is not viable on its own, and full development becomes feasible only under high CO_2 price scenarios, with pipeline CAPEX and capture costs as key sensitivities. The project faces uncertainties related to social acceptance, financing, and permitting but offers strong potential for regional CCS deployment in Poland.

Macedonia Basin (Greece):

The proposed CCS development in the Mesohellenic Trough follows a storageled concept in which CO_2 primarily originates from external industrial sources due to the declining availability of local emissions in Western Macedonia. The system integrates capture, transport and storage, with transport—mainly via dense phase pipelines—acting as the key link between remote emitters and the storage complex. Storage relies on deep saline formations of the Pentalofos and Eptachori units, offering more than 1 Gigatonne CO_2 capacity but characterized by moderate porosity and low permeability, making pressure management a central design constraint. A phased development approach progressively reduces geological uncertainties through characterization, pilot injection, and incremental scaling. Economic viability depends on injectivity, well count and stable CO_2 supply, while environmental and social assessments emphasize regulatory compliance, monitoring, public acceptance and alignment with Greece’s energy transition. Overall, feasibility hinges on controlled pressure behaviour, infrastructure integration and long-term CO_2 sourcing.

Table of Contents

3. Introduction

The PilotSTRATEGY project is investigating geological CO_2 storage sites in industrial regions of Southern and Eastern Europe to support development of large-scale carbon capture and storage (CCS). Research is focused on deep saline aquifers (DSA), which promise a large capacity for storing CO_2 captured from clusters of industry. The objective of the WP4 *"Pilot development and implementation plans"* is to provide and analyse available information of the optimum development concept applicable to the proposed pilots of the Paris Basin (FR), the Lusitanian Basin (PT), and the Ebro Basin (ES) to go ahead with the decision of whether these pilots are viable technically and commercially, considering social and environmental demands, and in the existing European and local regulatory frame. It will also enhance the knowledge of CO_2 storage options in the Western Macedonia region (GR) and Upper Silesia region (PL).

The definition of a possible development concept at these very early stages, where the uncertainties are very high and information could be very low, is not an easy task. To solve this and documented in the deliverable *D4.1: Methodology for alternatives definition, priorisation, and selection,* an approach inspired on the front-end loading (FEL) was applied based on WP2 (geological concept), WP3 (modelling and dynamic simulation) and WP5 (risk assessment and safety performance) results. This approach allows to integrate progressively the information required for a complete view of each pilot (technical, environmental, social, commercial, and regulatory), from a divergent thinking to a convergent thinking, ensures consistency in the proposals, identifies improvements, and maturates them to an optimized development concept ready for final decision. The process and conceptual scenarios for each region are described in the *D4.2 Conceptual scenarios definition to enable decision support; D4.3 Final concept description and preliminary considerations by regions; D4.4 Injector well and injection facilities design: methodology, definition, and recommendations; and D4.5 From capture to the injection facilities definition: capture, transport and* CO_2 *stream quality.*

The development concepts proposed by each region are defined on the social, environmental and regulatory frame identified by WP6 team (compiled on *D6.5 Summary report on public acceptance),* and WP4 tasks described on *D4.8 EIA report, and D4.6 Permit dossier: operations, logistics and well maintenance plans description, well permits road map, MMV plan and HSE, emergency response and well containment plans; and D4.7 Compiling of Environmental impact assessment legal frame and permit requirements for CO2 geological storage.*

The economic evaluation of the proposed development has been a key element for scenarios priorisation and selection of the optimum concept for each region. A common economical assumption and approach have been applied (*D4.9 Economic evaluation of alternatives and priorisation of results*) and refined by a probabilistic assessment and sensitivity analysis (*D4.11 Description and results of the probabilistic assessment and sensitivity analysis of the development concept*) which key results are analysed in this document.

Targeted to potential project developers, this report summarises the strategic information of each studied site for a documented decision about a possible implementation of a pilot based on the described development concept and its technical, economic, social, regulatory and environmental features.

4. Final proposal for a concept development by regions

In the PilotSTRATEGY project frame, *development concept or scenarios* refers to a technical description and planning of a possible CO_2 storage site development on the frame of local social interest, environmental restrictions, and regulatory considerations.

Every region developed and evaluated their region scenarios framed by its own objectives and, based on multicriteria decision, selected the best development concept for them using a fit for purpose approach: while the French team was focused on a pilot (pre-commercial) development, the Portuguese and Spanish teams have considered, in addition, a possible commercial development. Polish and Greek cases show a more general study for the full-life case. Therefore, the different regions development and timeframe are diverse from the very beginning, providing examples at various maturity stages for possible applications in the future.

A technical, economic, social, and environmental overview of the key elements for the proposed development for each region is here presented, providing a final analysis of the potential for each site for potential future developments.

4.1 Paris Basin (France)

4.1.1 Overview and context.

The French case was based on a hypothetical CO_2 pilot injection near-by a fertilizer plant which would emit 99% pure CO_2 at an estimated industrial rate (300 kt/y corresponding to the emission from a steam methane reformer) in the well-known Dogger formation from the Paris Basin. The pilot is designed to test technical feasibility, safety, and environmental compliance for a hypothetic large-scale CCS deployment. The hypothetical CO_2 pilot injection is limited to 100 kilotonnes (kt) according to article R229-61 of the French environmental code[1].

4.1.2 Executive summary

The Paris Basin CO_2 pilot project aims to demonstrate the technical feasibility and environmental impact assessment of injecting 100 kilotonnes of CO_2 into the Dogger (Oolithe Blanche) saline aquifer, leveraging a well-characterized geological setting with a thick and reliable Callovo-Oxfordian caprock. The project focuses on in-silico testing of safe injection operations, monitoring technologies, and regulatory compliance as a precursor to potential large-scale CCS deployment in the region.

Two CO_2 supply options are assessed: local CO_2 from a nearby fertilizer plant requiring onsite compression, and external CO_2 transported by rail. Two well placement scenarios—onsite (highly deviated well with wellhead within or near the fertilizer plant) and offsite (slightly deviated well with wellhead about 3 km away from the fertilizer plant)—are evaluated in terms of cost, operational constraints, and surface impact. Transport requirements are minimal, with only a 3 km high-pressure pipeline needed in the most demanding configuration.

Environmental and social assessments show no prohibitive constraints, with only moderate sensitivities related to water resources and existing infrastructure. Geological and dynamic modelling confirm that injected CO_2 remains well contained, with limited lateral plume migration (≤700 m) and

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[1] https://www.legifrance.gouv.fr/codes/article_lc/LEGIARTI000024739717

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

pressure effects dissipating within months after injection. No interference with existing wells or subsurface activities is expected.

Economically, the largest cost drivers are CO_2 conditioning or purchase as required for the pilot, well deviation, and monitoring. Offsite wells and external CO_2 scenarios are generally less expensive, though onsite well placement may offer advantages in land-use acceptability.

Overall, the project demonstrates strong technical feasibility, robust containment, minor to low environmental impact, and competitive long-term cost potential, supporting the Paris Basin as a promising candidate for future industrial-scale CCS development.

4.1.3 Proposed development

The scenarios considered for CO_2 pilot injection are summarised in Figure 4.1.

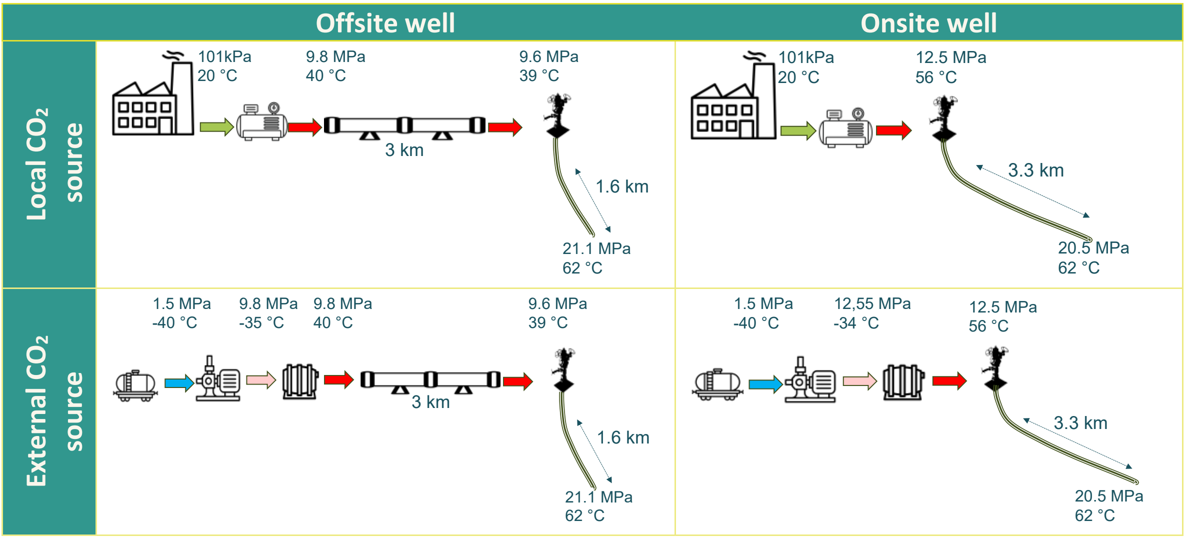

Figure 4.1 Development scenarios considered for a CO_2 injection pilot project in Paris Basin

The development of CO_2 pilot injection would require approval from the French regulatory authorities under the Environmental and Mining codes through the application for a “Permis Exclusif de Recherche” (Exploration permit). Such permit requires an assessment of the environmental, economic and social conditions of the area of interest along with its geological suitability for the foreseen operations.

4.1.3.1 Social and environmental assessment

The assessment was carried out to identify and evaluate the potential effects of the pilot CO_2 injection project on the physical, natural, and human environments throughout the different phases of the project, including both construction works and injection operations.

A comprehensive review of the environmental context within the study area was carried out as a baseline for CO_2 injection pilot to evaluate sensitive environmental components that could potentially be affected by the project and therefore require specific consideration in project design and implementation. The analysis shows that the study area is characterized by:

- a largely anthropized environment with moderate environmental sensitivities,

- no major constraints related to climate, topography, air quality, or noise,
- several medium-level sensitivities linked mainly to water resources (hydrogeology, surface water, water uses), natural risks, technological risks, and existing infrastructure.

Importantly, no highly sensitive or prohibitive environmental issue was identified within the area of interest.

For the physical environment, the project involves drilling to access the Dogger saline aquifer, well below all drinking water aquifers. The geological context, characterized by impermeable cap-rock formations and the absence of faults, combined with a multi-barrier well design and controlled drilling techniques, ensures the isolation of groundwater bodies. As a result, the risk of CO_2 migration toward freshwater aquifers or the surface is considered negligible.

Regarding the natural environment, the planned injection site and associated infrastructure are located outside of Natura 2000 sites and other protected areas. Although some sensitive natural environments, including rivers and a ZNIEFF area, are present within the wider study area, they will not be directly affected by the project. Potential impacts are mainly limited to temporary and localized disturbances during construction activities and are expected to be reversible.

With respect to people and local communities, the assessment identified potential short-term impacts related to construction works, such as noise, dust emissions, and increased traffic. These impacts will be limited in duration and managed through appropriate planning, monitoring, and compliance with regulatory and local requirements.

Considering the identified environmental issues, the characteristics of the project, and the different project phases, the impact assessment demonstrated that potential environmental impacts are limited and well understood. After implementation of avoidance, reduction, and compensation measures, residual impacts are expected to remain low across all environmental compartments. The detailed environmental, economic and social assessments are described in D4.8 (Canteli, 2026).

4.1.3.2 Capture

As part of its industrial process, the fertilizer plant is emitting 99% pure CO_2 during the steam methane reforming of natural gas to produce the hydrogen required for ammonia production (local scenario in Figure 4.1). However, the CO_2 conditioning at the plant would require a dedicated compressor and dryers to meet the well-head pressure conditions for injection.

Due to uncertainties on the plant activities, an alternate scenario considers external CO_2 delivery by train to the plant location (external scenario in Figure 4.1). As the CO_2 will be transported as a liquid, the CO_2 conditioning would require a dedicated unloading equipment along with a dedicated pump and heater.

The equipment designs with their energy and utilities characteristics are described in D4.6. *Permit dossier: operations, logistics and well maintenance plans description, well permits road map, MMV plan and HSE, emergency response and well containment plans (Canteli, 2026c).*

4.1.3.3 Transport

As the area of interest for the prospective pilot is located around the emitter, only a 3-kilometer-long CO_2 pipeline would be necessary in some of the considered scenarios as a function of the possible well-head location: within or near-by the plant (onsite scenario in Figure 4.1) or above the reservoir target (offsite scenario in Figure 4.1). The 6-inch pipeline would operate at high pressure (about 98 bar) and would mostly follow existing natural gas pipeline routes.

4.1.3.4 Storage

The area of interest for the CO_2 pilot project was studied in the past during the hydrocarbon exploration works. Despite of available data in the area (see D2.1 for a detailed inventory of the available data), some additional information was acquired to technically characterize the storage complex. New data was obtained from experimental and modelling studies on reservoir and caprock core in terms of their petrophysical characteristics and the interaction between CO_2-rich fluids and in-situ brine. The new 3D seismic improved the resolution of the geological structures and horizons as described in D2.3 (Bordenave, 2023).

After seismic interpretation and stratigraphic well analysis, the data were integrated within a geological model both in terms of structural elements such as seismic horizons after time depth-conversion and well markers, and their facies and petrophysical properties such as porosity, permeability, and shale content. The target formation is the Oolithe Blanche (Bathonian) in the Dogger, a carbonated ramp at about 1700-meter deep at a temperature of about 60°C and an initial pressure of about 185 bar. The ultimate cap-rock is the 120-meter thick Callovo-Oxfordian marls. The storage formation is characterized by strong lateral and vertical variations in porosity and permeability. Multiple realisations were performed to estimate a pessimistic, medium and optimistic case for the net porous volume as a proxy for the CO_2 capacity. The detailed results of the geological modelling are described in D3.2 (Bouquet, 2024).

An optimization workflow was used to determine the injection location to minimize interferences with surface and subsurface activities. Subsequently, an uncertainty analysis was carried out on the key parameters of the flow model e.g., permeability-porosity correlation, relative permeability parameters. The CO_2 pilot injection of 100 kt at a rate of 300 kt/year is achievable in most cases. In some extreme cases associated with the pessimistic model, the injection rate could not be maintained due to injection pressure limitation to prevent fracturing the formation. The corresponding pressure response may reach 70 bar in these cases. These few cases were later discarded accounting for well dynamic behaviour in the area; the pilot capacity is then verified without jeopardizing the system integrity in the studied context. The maximum overpressure is expected around 30 bar close to the injection well and extend up to 7 km for 1 bar perturbation in the extreme cases and less than 3 km for the best case. The pressure disturbances dissipate 8 months after the end of injection. The CO_2 plume migration is limited to about 350 m from the injection location while its vertical migration is also constrained by internal flow barriers and limited to about 90 meters within the Bathonian formation. The plume never reaches the caprock during the injection and 8 months post injection during the pressure dissipation. The detailed results of the dynamic modelling and well placement are described in D3.3 (Chassagne, 2024) and D3.5 (Bouquet, 2026).

The pilot simulation results indicate that structural trapping predominates initially, accounting for approximately 85–90% of the stored CO_2. However, a progressive shift toward more stable trapping mechanisms is observed over time. After 1000 years, solubility becomes the dominant mechanism, trapping approximately 70–75% of the CO_2, followed by residual trapping, which accounts for 20–22%. Structural trapping reduces to around 10% by this time. These findings highlight an enhancement in storage security over time, as dissolution progressively immobilizes the injected CO_2.

During the injection period, the CO_2 does not reach the cap rock and continues to migrate upward during the following years. It takes around 11 years for the dissolved CO_2 to reach the Massingy marls (base of caprock). After 500 years, CO_2 does not penetrate any further than the base of caprock. The geochemical modelling of the caprock exhibits limited dissolution of minerals such as calcite and chlorite, along with dolomite precipitation, indicating pH buffering mechanisms and a minor reduction in porosity. There is a negligible geochemical impact on the caprock of the CO_2 pilot injection. The detail description of the long-term evolution of the CO_2 is available in D3.5 (Bouquet, 2026).

A probabilistic quantitative assessment was carried out for the CO_2 injection pilot including safety risk events such as leakage through existing wells, caprock integrity, other subsurface uses, performance indicators such as lateral extent of the plume, storage capacity, and injectivity. The quantitative risk assessment for the CO_2 injection pilot does not show any significant subsurface risk and interference with legacy wells or subsurface activities even over the long term (1000 years) as detailed in D5.2 (Le Guenan and Ben Rhouma, 2026).

Considering the target location in the Oolithe Blanche and surface constraints, two scenarios (Figure 4.1) are considered for the wellhead location either onsite with a long and strongly deviated well or off-site about 3-km away with a slightly deviated well. The wellhead conditions are computed based upon the two designs to estimate the required compression at the plant. The 40-meter perforated interval in the target formation, Oolithe Blanche (Bathonian), is defined as recommended in the dynamic simulations performed for both scenarios using a 4½-inch liner in a 7-inch production casing. The well sections are defined to protect sensitive Albo-Aptian aquifer covered by 2 casings, cemented up to surface. The well architecture requires 4 or 5 casing stages for the offsite and onsite cases respectively. For the offsite case, the well deviation is about 26° while for the onsite case the deviation is about 65°. The well architectures along with the casing, tubing and completion characteristics are detailed in D4.5. The data acquisition during drilling is slightly different depending on the case and is minimal above the Callovo-Oxfordian caprock and more thorough within the Callovo-Oxfordian caprock and Bathonian storage formations with open and cased-hole logs, core and fluid sampling. After completion, an extended brine injection test is planned to assess the formation injectivity and flow barriers. The details are shown in D4.6 (Canteli, 2026c).

4.1.3.5 Monitoring

The planned Measurement, Monitoring, and Verification (MMV) program addresses the key concerns of the storage complex and surface installations following the project qualitative risk assessment for the CO_2 injection pilot. Different technologies and frequency of acquisition were defined as illustrated in Figure 4.2 and detailed in D4.6.

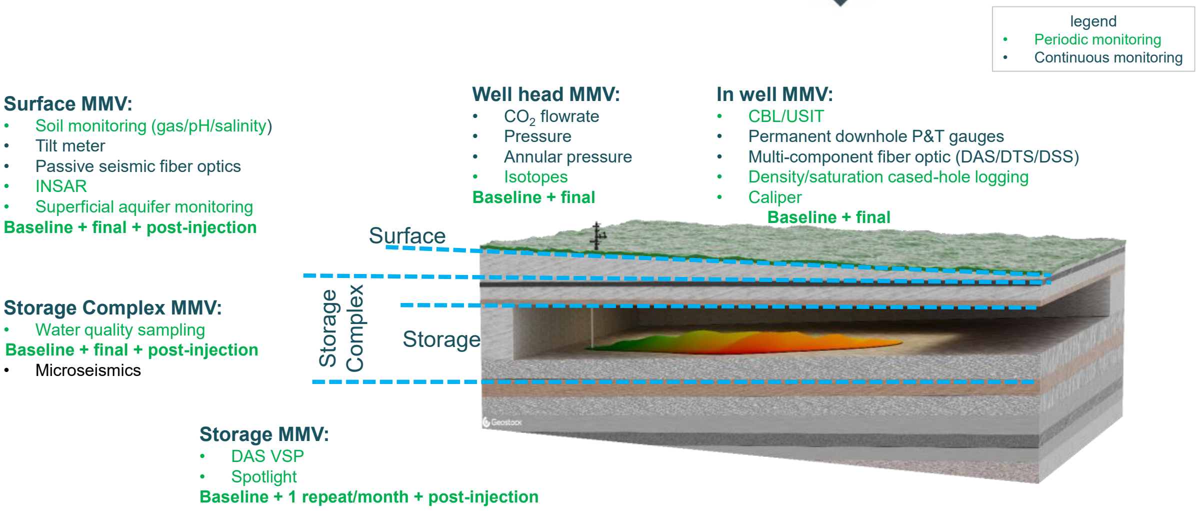

Figure 4.2 Monitored subsystems of the geosphere for a CO_2 injection pilot project in the Paris Basin

4.1.4 Proposed planning

As detailed in D4.6 (Canteli, 2026c), the planning shall account for the administrative review of the exploration permit request and subsequent time for long-lead items. It was considered that such procurement would only take place once the permit is granted. In addition, the monitoring would be required while the CO_2 is migrating as imposed by the CCS Directive and its guidance documents which may last up to 8 years according to the modelling results from D4.6.

When including the dismantling of the surface installation and well abandonment in accordance with regulatory requirements, the pilot project extends 10 years after filing the exploration permit as recalled in Figure 4.3.

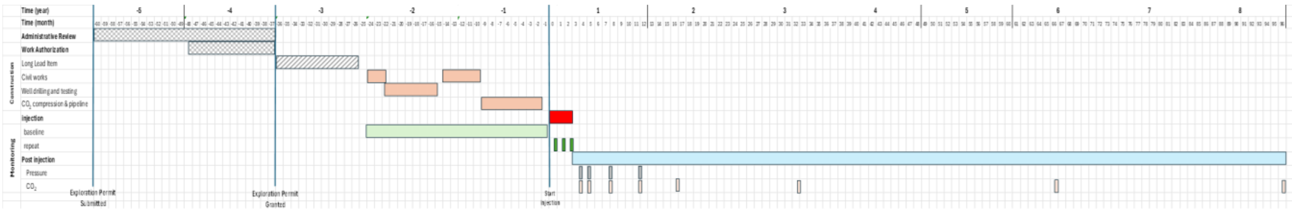

Figure 4.3: Foreseen life cycle planning for a CO_2 injection pilot from administrative filing to post closure monitoring.

4.1.5 Economic assessment

A probabilistic class IV (accuracy range −30% to +50%) cost assessment was carried out and detailed in D4.11. The main economic drivers of the scenario for a CO_2 injection pilot are:

- Compressor CAPEX (scenario with local CO_2 in Figure 4.1) vs. CO_2 purchase cost (scenario with external CO_2 in Figure 4.1).
- Well deviation (for the onsite scenario in Figure 4.1 vs for the offsite scenario in Figure 4.1).
- Monitoring for the storage and storage complex (Figure 4.2)

The scenarios with onsite well (Table 4.1 and Figure 4.4) are generally more expensive than the scenarios with offsite wells due to drilling and well completion costs. The scenarios with local CO_2 (Table 4.1 and Figure 4.4) are generally more expensive than the scenarios with external CO_2 due to compressor costs significantly larger than CO_2 purchase costs. However, there may exist market constraints on CO_2 availability over a short time period.

Considering the recent evolution of the industrial activity of the fertilizer plant and the suggestion from local stakeholders to minimize the land impact of the project, the onsite well with external CO_2 is an interesting alternative to the less expensive case (offsite well with external CO_2) as the two distributions partially overlap given the level of uncertainties as shown Figure 4.4.

Scenario	Offsite total cost (M€$_{2025}$)			Onsite total cost (M€$_{2025}$)		
	P10	P50	P90	P10	P50	P90
Local CO_2	64	74	85	67	76	88
External CO_2	41	45	50	45	49	53

Table 4.1 Distribution of the CO_2 pilot project cost (CAPEX+OPEX+ABEX) (M€$_{2025}$) for the various scenarios

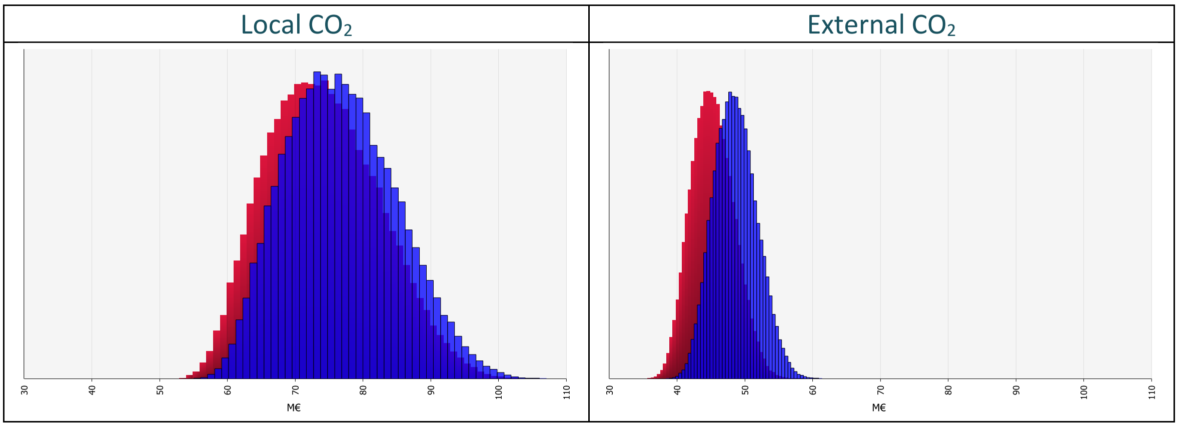

Figure 4.4 Distribution of the CO_2 pilot project cost (CAPEX+OPEX+ABEX) (M€$_{2025}$) for CO_2 pilot for the local CO_2 (left) and external CO_2 (right) with the offsite well (red distribution) and the onsite well (blue distribution). The distributions are reported with the same scale ranging from 30 to 110 M€$_{2025}$.

4.1.6 Perspectives

Beyond the hypothetical CO_2 pilot, the main economic perspective would be the development of a commercial storage project which only considers external CO_2 availability due to changes in the industrial strategy of the fertilizer plant. Such commercial storage project would be elaborated based upon the pilot results and would require regulatory approval for a CO_2 storage concession.

The hypothetical commercial case was based upon the same assumptions as the CO_2 injection pilot i.e. same injection rate (300 kt/y) for 30 years, i.e. 9 Mt of CO_2, followed by a 1000-year long term evolution phase as detailed in D3.4 (Ben Rhouma, 2026). The optimistic scenario resulted in a vertical plume extension ranging from 125 m to 135 m, while the lateral extension was approximately 2.6x2.8 km^2 at the end of injection, subsequently evolving to 3.6 x 4.8 km^2 after 1000 years. The maximum overpressure was estimated to be about 13 bar in the vicinity of the well, and a perturbation of less than 1 bar extends over about 6 km at the end of the injection period. Notably, the overpressure dissipated within about 15 years following the end of injection. The probabilistic quantitative assessment carried out for the commercial case showed that the main risks are related to the integrity of three legacy wells in the area which should be investigated as detailed in D5.2 (Le Guenan and Ben Rhouma, 2026). A potential interference with currently active oil licences, which are expected to end operations in 2040[2], might occur depending on the starting date of the hypothetical commercial case.

For the commercial-scale project, it is assumed that deep monitoring wells (5) will be required on the edge of the expected plume evolution and one well in the first aquifer above the caprock, thus modifying the CAPEX of the commercial-scale project. The monitoring strategy is assumed to use the some of the technologies used for the pilot but at a different frequency during the injection and post injection periods, every 5 years for DAS-VSP during the pressure increase period and every 10 years beyond, soil and water sampling and electromagnetic logs except for micro-seismic monitored continuously and INSAR monitored yearly during the pressure increase period. As shown in Table 4.2, these strategies modify the OPEX and consequently the overall costs of the commercial-scale project.

Offsite total cost (M€$_{2025}$)			Onsite total cost (M€$_{2025}$)		
P10	**P50**	**P90**	**P10**	**P50**	**P90**
55	59	63	57	61	66

Table 4.2 Distributions of the CO_2 commercial project cost (CAPEX+OPEX+ABEX) (M€$_{2025}$) for the external CO_2 scenarios

The commercial development costs (Table 4.2) that may follow the CO_2 pilot injection could be estimated between 9.1 and 10.9 €$_{2025}$/t$_{CO2}$. This expected cost for industrial scale development may be compared to recent public estimates [GCCSI, 2025]: the location selected for the hypothetical CO_2 injection commercial scale project would correspond to the “open boundary” aquifer with good to medium reservoir quality as shown in Figure 4.5.

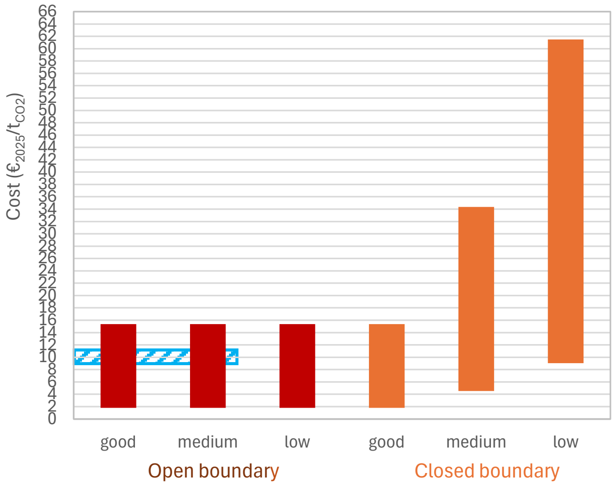

Figure 4.5 Estimated costs of CO_2 for a 1 Mtpa commercial onshore project as a function of the reservoir quality (adapted from GCCSI 2025) where the dashed areas correspond to the 0.3 Mtpa commercial scale project for Paris Basin for the external CO_2 (blue shade)

4.1.7 Risk-benefit assessment.

A SWOT analysis on the hypothetical CO_2 pilot project is shown in Table 4.3. The strengths (S) and weaknesses (W) are internal factors to the pilot project, whilst opportunities (O) and threats (T) are external factors.

Strengths	**Weaknesses**
• Proven caprock and storage	• No lateral confinement
• Industrial platform within a rural area	• Cost of the pilot

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[2] Law n° 2017-1839 on 30 Decembre 2017 changing article L. 111-9 of the French mining code.

• Low technical and HSE risks to surface and subsurface • Thorough MMV plans	• Uncertainty about CO_2 source and purchase cost for the pilot
OpportunitiesCommercial-scale deployment • Limited CO_2 lateral extension • Neighbouring oil licenses may not be active at start of commercial scale development • Enabling carbon neutral industrial activities • Existing connections (rail, road, pipeline) may develop as storage hub	**Threats** • Exploration license application already filed • Local opposition towards CCS • Lack of perceived local benefits induced by the pilot • Uncertainty in CCS policy support • Uncertain access to EU/national funds for the pilot

Table 4.3 SWOT analysis of the Paris Basin CO_2 pilot project

4.2 Lusitanian Basin (Portugal)

4.2.1 Overview and context

The Portuguese case consists of an offshore CO_2 pilot injection project in the northern sector of the Lusitanian Basin, located about 22 km offshore from the city Figueira da Foz. The pilot is intended to validate: (i) injectivity and pressure behaviour in the selected reservoir; (ii) plume development and containment performance; (iii) feasibility of offshore monitoring and environmental surveillance; and (iv) practical interaction between geological, maritime and environmental regulatory domains for future commercial CCS deployment.

The Portuguese pilot is both a technical demonstration and a strategic enabling step: **it addresses a gap in national CO_2 storage readiness and supports the longer-term needs of hard-to-abate sectors under Portugal's carbon neutrality pathway to 2045.**

4.2.2 Executive summary

Portugal has committed to achieving carbon neutrality by 2045. Achieving this objective requires deep decarbonisation across several hard-to-abate industrial sectors, including cement, lime, waste management and chemicals, but also provide opportunities for negative emissions notably from the pulp & paper sector. Carbon Capture and Storage (CCS) is increasingly recognised as a key enabling technology for decarbonising these sectors. However, Portugal lacks operational CO_2 storage capacity. Thus, a pilot CO_2 storage project is a necessary step toward enabling future CCS deployment.

PilotSTRATEGY proposes the implementation of an offshore CO_2 storage pilot in Portugal targeting the Q4-TV1 prospect in the Lusitanian Basin offshore Figueira da Foz (Figure 4.6). The pilot will inject up to 100 ktCO_2 as part of a research and demonstration project that integrates capture assumptions, modular logistics, a single-well injection system, and an extensive MMV plan. The project focuses on pilot-scale testing of safe injection operations, monitoring technologies and regulatory compliance as a precursor to any future industrial-scale CCS deployment in Portugal.

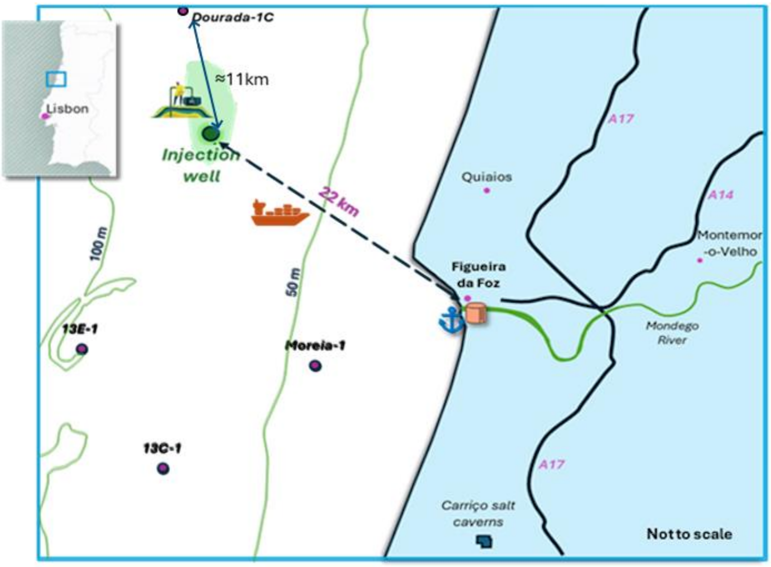

Figure 4.6: Location of the CO_2 pilot.

The CO_2 for the pilot will be sourced from the Souselas cement plant, with a back-up provided by pulp & paper sources near Figueira da Foz. The pilot design considers multimodal rail and ship transport of CO_2 in cryogenic containers and direct injection from the vessel. **This avoids permanent pipeline and platform infrastructure at pilot stage and prioritises flexibility, reusability of equipment and minimal irreversible investment**.

The storage reservoir is located in Lower Cretaceous siliciclastics of the Torres Vedras Group / Figueira da Foz Formation, at more than 850 m below mean sea level, and is overlain by a competent regional seal. Modelling and long-term fate analyses support containment within the storage complex and show a progressive transition toward more secure trapping mechanisms over time. The safety and performance assessment concludes that the pilot can be operated with a very low risk profile, with no significant risks, provided the proposed MMV and corrective-measures framework are implemented.

The pilot is learning-oriented with a concern about social and environmental impacts and that needs to be developed in close cooperation with regional stakeholders. Environmental and social pre-assessments show no prohibitive constraints at concept stage, with the main sensitivities linked to marine environmental baseline definition, compatibility with maritime uses, port handling and the temporary impacts of offshore works. The offshore location limits direct interactions with populated areas, while the pilot scale and temporary infrastructure reduce the footprint.

Economically, the main cost drivers are offshore drilling and completion, the ship-to-well injection system, rail and maritime logistics, and the seismic and MMV programme required to qualify the storage complex and support future upscaling**.** The class IV cost assessment indicates a most-likely **total investment of approximately €98 million, with the pilot being implemented from 2027-to 2033.**

Strategic Dimension	Contribution of the Pilot
Climate Policy	Supports Portugal's objective of achieving carbon neutrality by 2045
Industrial Competitiveness	Enables decarbonisation pathways for hard-to-abate industrial sectors
Infrastructure Development	First step toward future CO_2 transport and storage infrastructure
European Integration	Positions Portugal within emerging European carbon management networks

Table 4.4 - Pilot main characteristics

4.2.3 Proposed development

The context is strongly influenced by three boundary conditions. First, Portugal has committed to achieving carbon neutrality by 2045, which increases the relevance of CCS for hard-to-abate sectors. Second, the country does not yet have operational CO_2 storage capacity. Third, there are significant regulatory challenges for conducting offshore storage in the country. Thus, the pilot is designed as a research and demonstration project aiming to inject up to 100 ktCO_2 while maintaining robust safety and monitoring[3].

4.2.3.1 Capture

The pilot-scale capture assumption is based on the availability of an industrial CO_2 stream from the Souselas cement plant. A possible back-up CO_2 source, if the capture pilot is not implemented at Souselas in due time, is provided by the pulp & paper factories near Figueira da Foz. Because the Portuguese pilot is conceived as a research and demonstration project, the emphasis is not on optimising capture economics, but on ensuring availability of a technically suitable CO_2 stream. Thus, PilotSTRATEGY does not design the capture component, but it considers the conditioning chain (Figure

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[3] Article 2, paragraph 3, of Portuguese Decree-law 60/2012, which translates the EU Directive 2009/31/EC on CO_2 Geological Storage (CCS Directive) exempts projects injecting less than 100 kt for research purposes from the licencing procedures for CO_2 storage

4.7), which includes compression, dehydration and liquefaction to approximately 15 bar and -29 °C and loading arrangements consistent with the selected transport concept.

4.2.3.2 Transport

CO_2 is transported from the capture facilities to the port of Figueira da Foz by rail and then shipped to the offshore injection site, with direct injection from the vessel and avoiding permanent pipelines, offshore platform and intermediate storage installations. The pilot considers a rail distance of about 55 km from Souselas to the port and a maritime distance of about 22 km from port to injection site. Around 650 tCO_2/day will be transported and injected under the design assumptions, corresponding to 152 round trips to deliver 99 $ktCO_2$. The injection phase is expected to last up to about 15 months. The foreseen chain includes (Figure 4.7Figure 4.18):

- transfer of conditioned/liquefied CO_2 to rail-compatible cryogenic containers;
- rail transport to the port of Figueira da Foz;
- handling at port to transfer containers to vessel;
- maritime transport to the offshore pilot site;
- direct connection of the vessel to the wellhead for direct injection.

Although operationally more complex than a fixed pipeline solution, this modular logistics chain is well suited to a first pilot because it limits infrastructure and maximises flexibility. This configuration also provides operational experience that may be relevant for large-scale CO_2 logistics systems that may include ship-based transport from CO_2 sources further south in the country.

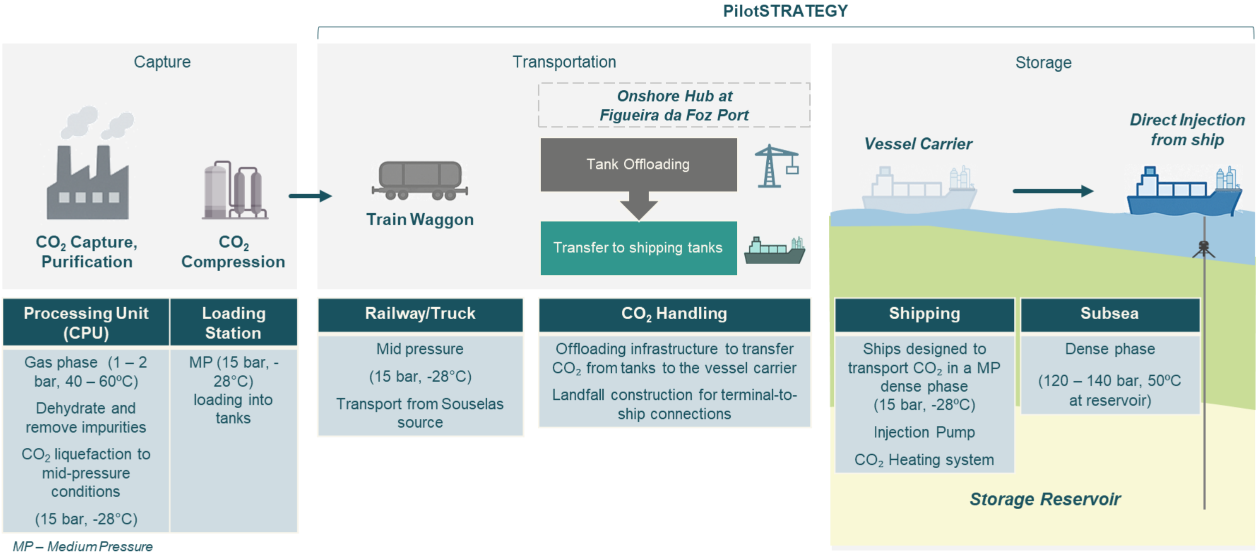

Figure 4.7: Pilot components. CO_2 conditioning is indicative and may change according to operational conditions.

4.2.3.3 Storage

The selected storage concept is based on CO_2 injection into the Q4-TV1 prospect located in the offshore Lusitanian Basin, at shallow waters (85m). The target reservoir corresponds to the Torres Vedras Group / Figueira da Foz formation, composed predominantly of sandstones and conglomerates, at depths of approximately 850 to 1200 m below mean sea level, providing suitable and safe conditions for CO_2 injection.

Containment is ensured by a multi-barrier sealing system identified in the project safety assessment (D5.4 – Carneiro et al., 2026). The primary seal is formed by the Cacém Formation, consisting of low-permeability marls, carbonates and clay-rich lithologies, directly overlying the reservoir. This is complemented by a secondary seal composed of overlying Aveiro formation, providing an additional thick barrier and enhancing long-term containment robustness. This stacked sealing configuration is a key factor supporting the security of the structure for CO_2 storage.

Reservoir analysis indicates favourable injectivity conditions, with estimated well injectivity ranging between approximately 0.5 and 1.1 $MtCO_2$/year. The total storage capacity of the Q4-TV1 site and surrounding area is estimated at 93 $MtCO_2$, confirming that the site is suitable for future scale-up.

The pilot is designed around a single offshore injection well, with injection conditions optimised through reservoir modelling, with the pilot injection intervals planned at around 1155 m and 1205 m depth. The injection strategy ensures that reservoir pressure remains below 165 bar, thereby preventing excessive overpressure and reducing risks of caprock failure or fault reactivation. The selected well location also ensures that the simulated CO_2 plume remains at a safe distance from the legacy well Do-1C, with modelling results showing no plume interaction across all evaluated scenarios. In addition, regional data indicate low seismic activity in the area, and adequate pressure management ensures the risk of induced seismicity to remain very low.

The long-term fate of injected CO_2 is characterised by a rapid transition from mobile to immobilised phases. During injection, storage is dominated by structural trapping (80%), with 15–20% dissolving. After injection, pressure declines quickly (to around 130 bar), limiting plume migration. Residual trapping becomes dominant (60–70%) over decades to centuries, while solubility increases to 25–30% over 1000 years. Structural trapping decreases to negligible levels (<5%) and mineral trapping remains minor (<1%). Overall, rapid pressure dissipation and trapping evolution strongly reduce CO_2 mobility, ensuring confinement and increasing long-term storage security.

A key objective of the storage component is to generate high-quality data for validation of reservoir behaviour and containment performance. The pilot will therefore implement a comprehensive Measurement, Monitoring and Verification (MMV) system, designed to address the main uncertainties identified in the reservoir simulations (D4.6 - Canteli, 2026c), including pressure evolution, plume migration, containment integrity and marine environmental observations. The MMV plan integrates:

- 3D seismic reflection data for baseline definition, DAS-based surveillance, and Spotlight™ to track plume development and spatial extent;
- downhole pressure and temperature monitoring to verify reservoir response and pressure management;
- natural and induced seismicity monitoring, with Traffic Light System for decision making;
- well integrity monitoring systems to ensure containment at the injection well;
- marine environmental baseline and follow-up observations to detect offshore impacts.

This MMV approach allows direct comparison between model predictions and observed behaviour, providing a robust basis for validating the reservoir and containment operating conditions.

4.2.4 Proposed planning

The planning of the Portuguese pilot accounts for maritime authorisations, environmental procedures, seismic vessel scheduling, offshore drilling capacity and rail-port-injection logistics. The pilot extends from 2027 to 2033 (Table 4.5), in a phased process with GO /NO GO decision gates to reduce investment risks.

Period	Phase
2027–2028	Permitting, EHSIA, environmental baseline, tender for 3D seismic and pre-FEED
2028–2029	Seismic acquisition, geological refinement, engineering and MMV detail
2029–2030	Procurement, permitting and preparation for offshore works
2030	Drilling and completion of the injection well
2031–2032	CO_2 injection operations
2032–2033	Post-injection monitoring and evaluation

Table 4.5 - Pilot schedule

This schedule remains indicative and subject to uncertainty, particularly with respect to permitting timelines, procurement and offshore operational windows. Still, the **phased approach enables gradual validation of technical and regulatory aspects before committing to full-scale development.**

4.2.5 Economic assessment

A detailed probabilistic Class IV cost assessment was carried out for the Portuguese case, following the common PilotSTRATEGY economic frame. The offshore nature of the project and the absence of existing infrastructure are the primary drivers of cost at pilot-scale.

Component	CAPEX (M€)	OPEX (M€)	SUB-TOTAL (M€)
CO_2 Conditioning	3.7	0.9	4.6
Train and Port Operations	-	4.3	4.3
Shipping and Operations	3.0	11.4	14.4
Subsea (connection ship to well	25.0	1.3	26.3
Drilling & Completion	30.0	1.5	31.5
3D Seismic Acquisition	13.8	-	13.8
ABEX	-	-	3.1
Total			**98**

Table 4.6 - Summary table with the reference cost estimation

The most-likely total investment (CAPEX + OPEX + ABEX) is approximately €98 million (Table 4.6), with an overall range of roughly €90–120 million. Costs are dominated by drilling and completion, subsea systems and 3D seismic acquisition, while operating expenditure is mainly driven by transport, shipping and offshore injection operations. **The economic rationale therefore lies primarily in de-risking and option value rather than in short-term storage service economics.** That is, the investment case must be understood as a preparatory infrastructure step for future CCS deployment in Portugal.

4.2.6 Social and environmental assessment

The pilot will serve as a test case for defining appropriate monitoring protocols for offshore CO_2 storage in conditions of the Portuguese offshore. The social and environmental assessment indicates no prohibitive constraint at concept stage but confirms that marine baseline definition and monitoring are central to project acceptability. The offshore pilot shifts the main sensitivities away from direct land-use conflicts and toward offshore environmental receptors, maritime-use compatibility and port-related handling. The main issues identified include potential temporary disturbance during seismic data acquisition and offshore works, interactions with benthic habitats and water-column chemistry, and the need to demonstrate that project-related perturbations (3D seismics, drilling, MMV) remain within acceptable and reversible limits.

The proposed mitigation logic is based on early environmental baseline surveys, a vertically integrated MMV design, careful scheduling of offshore operations, and coordination with maritime users (e.g. fishermen) and competent authorities. Overall, the environmental and social impacts are manageable and do not constitute a show-stopper, provided that monitoring, mitigation measures and stakeholder engagement are implemented and transparent.

4.2.7 Risk-benefit assessment

In risk-benefit terms, the Lusitanian Basin pilot combines a strong strategic upside with the expected challenges of a first-of-a-kind offshore demonstration, as stressed by the SWOT analysis (Table 4.7).

Strengths	**Weaknesses**
• identified offshore storage prospect in the Lusitanian Basin; • strong strategic relevance for long-term Portuguese CCS readiness; • research-scale design adapted to current regulatory constraints; • modular logistics concept limiting the need for permanent infrastructure at pilot stage.	• high unit costs due to first-of-a-kind offshore pilot development; • remaining uncertainties regarding detailed geological performance and offshore execution; • complexity of the intermodal logistics chain; • Regulatory issues
Opportunities	**Threats**
• creation of the first operational experience with geological CO_2 storage in Portugal; • generation of technical and regulatory knowledge needed for future commercial projects; • support for hard-to-abate sectors under a carbon neutrality pathway; • potential positioning of Portugal within future European carbon management networks.	• delays associated with offshore permitting and coordination across authorities; • cost escalation in offshore drilling or logistics; • higher-than-expected environmental monitoring requirements; • insufficient continuity from pilot stage to commercial follow-up.

Table 4.7 - SWOT analysis of the Lusitanian Basin CO_2 pilot project

4.2.8 Scale-Up Potential

The pilot is explicitly framed as Phase I of a two-phase development pathway for offshore CO_2 storage in the Lusitanian Basin, with Phase II corresponding to commercial deployment once subsurface behaviour, offshore operability and regulatory framework have been de-risked. Commercial operation is expected from 2035 onwards, with an initial injection envelope of 0.5–1.1 $MtCO_2$/year in the pilot injection well, and progressively expand toward a national scenario integrating CO_2 from 14 industrial sources across the cement, lime, oil refining, waste management and pulp & paper sectors. A detailed source-level assessment indicates a maximum of 9.3 $MtCO_2$/year available for capture and storage in the 2035–2065 timeframe, of which nearly 60% is biogenic, enabling negative emissions.

The transition to Phase II involves a shift from modular logistics (rail and ship-based transport) to dedicated transport infrastructure. Pipelines will form the baseline configuration for both onshore and offshore transport, with a pipeline network of approximately 700 km, developed along the coastal region, reflecting the spatial distribution of major emission sources. Ship-based transport solutions may remain relevant for more distant CO_2 sources. Infrastructure development is anchored at pipeline landfall south from the Figueira da Foz port, where a permanent reception and injection hub is foreseen, including reconditioning, pipeline launch systems and monitoring facilities[4,5].

At this stage, the system evolves from a single-well pilot configuration to a multi-well storage development, requiring additional injection wells and the utilisation of multiple storage sites within the Lusitanian Basin.

Overall, the scale-up pathway corresponds to the development of a cluster-based CO_2 transport and storage system, progressively integrating multiple industrial sources and expanding storage capacity within the Lusitanian Basin.

4.2.9 Regulatory needs and challenges

The development of offshore CO_2 storage involves multiple regulatory bodies and requires coordinated consideration of, at least:

1. DGEG - CO_2 storage regulation and licensing;
2. DGRM - permitting of maritime spatial planning and offshore operations;
3. APA - environmental assessment and monitoring.

As no CCS projects have yet been implemented in Portugal, coordination mechanisms between these authorities should be implemented during the pilot, providing an opportunity to establish a coherent and streamlined permitting pathway.

While the pilot can be implemented within the existing framework as research and demonstration, the transition to commercial-scale CO_2 storage requires addressing regulatory challenges. A first key requirement concerns the integration of CO_2 storage into the PSOEM[6]. The current PSOEM does not explicitly allocate areas for geological CO_2 storage. The development of an allocation plan identifying suitable offshore areas will therefore be necessary to enable large-scale deployment.

A second challenge relates to the governance of offshore subsurface resources. CO_2 storage reservoirs fall within the broader category of mineral deposits, yet responsibilities for mineral deposits in the maritime space are, currently, not clearly defined[7]. Clarifying institutional competences will be essential for a consistent permitting framework. Finally, it is necessary to explicitly confirm that CO_2 storage is not subject to the deep-sea mining moratorium[8], in order to avoid legal ambiguity.

Lastly, Portugal does not have a dedicated regulatory framework for CO_2 transport by pipeline. While future European Union legislation may provide a common basis, it is essential that permitting procedures, technical standards and responsibilities for transport infrastructure are clarified at national level within a timeframe compatible with the start of commercial operations.

The main constraints for future scale-up are now primarily institutional, notably in maritime planning for CO_2 storage, subsurface governance, legal clarity and inter-authority coordination.

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[4] Mesquita et al. (2026) - Techno-economic evaluation report. Deliverable D3.1, CTS project.

[5] Mesquita et al. (2026) - Techno-economic evaluation report. Deliverable D3.1, CTS project.

[6] Portuguese Maritime Spatial Plan, established by the Resolution of the Council of Minister 203-A/2019.

[7] Decree Law 30/2021 in its Article 3, paragraph 2, refers that the mineral deposits located in the national maritime space are subject to special legislation. However, it does not revoke the Decree Law 60/2012, which attributes to the Directorate-General for Energy and Geology (DGEG) the competence to act within the established legal framework concerning the CO2 storage.

[8] Law 36/2025 establishes a moratorium on deep-sea mining until 1 January 2050, including prospecting and exploration activities.

4.3 Ebro Basin (Spain)

4.3.1 Overview and context

The Ebro Basin case studies an onshore site (the Lopín structure, Spain) to assess as a potential geological storage site for CO_2. The area is located at north-east of Spain, in a very low populated area (3 small village of 1500 inhabitants at 10 km distance), with no agriculture or farming developments near-by, and potential emitters (paper industry and energy valorisation) in a 60 km radio. National data identify this area as a very low natural seismicity activity.

The Lopín subsurface has been investigated in previous projects (ALGECO2, Strategy CCUS) and offers a favourable geological setting: a deep saline aquifer with good areal extent and competent overlying seals (Triassic clays and evaporites) that isolate the reservoir from shallow formations. The storage capacity range was estimated between 2 Million tonnes (Mt) and 35 Mt considering existing information and uncertainties.

Ebro Basin study is focus on the store site exploration and development, including an exploration phase, a pre-commercial phase (pilot), and a commercial phase analysis, with the objective of (1) evaluate the impact of a significant geological uncertainty, (2) define a development strategy that better fits to move Lopín site from a pilot to a commercial development, and (3) evaluate deterministic and probabilistic techno-economic viability of a commercial development based on a realistic schedule activities and costs as base for future decision makers.

CO_2 capture and transport design and costs are not included in this analysis, and only for scenario validation reason, a valid option has been identified in both cases. It is assumed that the delivered CO_2 meets appropriate specifications.

4.3.2 Executive summary

The CO_2 storage project in the Ebro Basin proposes the full life cycle analysis of an onshore structure including exploration phase, a 3-year injection pilot or pre-commercial phase, and a commercial development phase. Lopin site is a deep saline aquifer of Triassic age at north-east of Spain, in Belchite area (province of Zaragoza, Spain), a siliceous sandstone at ~1,700 m depth beneath a thick clay-rich seal. Although the primary seal is not well documented, a secondary and regional caprock is well defined and ensure a barrier for a potential leakage. On the other hand, the storage formation of the Lopín structure exhibits natural overpressure and low permeability, giving a narrow operational margin before reaching the fracture pressure of the primary caprock.

Existing geological data are from 1970- 1980 and, although the regional geology is well known, new data are needed for reducing current geological uncertainties, reason for starting the evaluation with a data acquisition through an exploration phase. Assuming a geological success, a pilot development is defined by injection of 100 kt of CO_2 over approximately 3 years through a single well, which would make it possible to evaluate, under real conditions, the reservoir response, the effectiveness of the geological seal, and CO_2 monitoring techniques. Initial studies indicate that the reservoir can accommodate this pilot injection without significant risks. Assuming storage site validation, a commercial development is carried out, operating until estimated capacity is reached and site is abandoned, with an estimated capacity range between 2 Mt and 35 Mt.

Exploration, pilot and commercial phases are evaluated techno-economically by deterministic and probabilistic approach to cover the full range of uncertainties and the impact on economic decision-making parameters for the pre-investment proposal.

4.3.3 Proposed development

Following the methodology applied in Paris Basin and Lusitania Basin, the Spanish team has defined a pre-commercial scenario (exploration phase and pilot with a total injection of approximately 100,000 tonnes of CO_2 over 3 years through a single well) and, contingent on the success of this, a larger-scale commercial scenario with one or two injector wells depending on total estimated capacity, between 2 to 35 million tonnes. In both cases, pilot/precommercial and commercial, the availability of CO_2 from a nearby industrial source is assumed; therefore, capture and transport costs are not included in this analysis, and it is assumed that the delivered CO_2 meets appropriate specifications. This isolated approach makes it possible to realistically assess the technical and economic feasibility of storage at Lopín, by comparing minimum versus expanded development alternatives. The overall objective is to determine whether the Ebro site can progress towards a technically and commercially viable carbon capture, transport and storage (CCS) solution within the current Spanish and European regulatory framework, based on a deterministic and probabilistic evaluation for decision making.

Figure 4.8: Pilot and commercial development scheme.

- **Exploration phase:**

Starting with an exploratory permit requested in 2027, a G&G study, 2D/3D seismic survey and interpretation, and exploratory well design, drill and tests are included in the exploration phase. Total exploration phase duration is estimated between 4 and 6 years.

- **Pilot phase (pre-commercial or demonstration):**

This consists of the controlled injection of 0.1 Mt of CO_2 (around 100,000 tonnes) over 3 years through a single injection well. The CO_2 is assumed from a local industrial source (there are several candidate emitters in the region in a 60 km radius). From a practical point of view -but no included in the economic analysis- this logistical approach (onshore trucking) is viable for volumes of 30 kt/year and provides flexibility while storage performance is being validated. At surface, a mobile pumping and compression station will be installed to bring the CO_2 to injection conditions (dense supercritical phase, typically 80–100 bar and 30 C). The pilot well design envisages a vertical well completed in the deep saline reservoir horizon. CO_2-resistant steels and cements will be used to isolate the permeable layers crossed, and an 8½" production casing will be installed across the reservoir interval, ensuring integrity against corrosion.

During low-rate injection (around 30 kt/year of CO_2), intensive monitoring will be implemented, with advanced instrumentation deployed (fibre optics for temperature and seismic monitoring, downhole pressure sensors, etc.). The pilot phase includes 1–2 initial years of design, permitting and construction (authorisations, engineering, drilling), followed by 3 years of injection and monitoring operations. Upon completion of the test injection, technical results and environmental performance will be analysed and taking the decision of going ahead or abandoned.

- **Commercial phase (full scale):**

Ebro basin study is focussing on the storage site, and capture and transport design and evaluation are outside of the scope of this study. However, both capture and transport possibilities have been considered to validate defined scenario, identifying available sources in the area and potential transport possibilities to CO_2 deliver, at required conditions, in the injection facilities reception. In that case, Ebro Basin case defines exploration activities, injection facilities design and construction, injector well(s) design and drilling, MMV plan and implementation, and storage site management, including abandonment.

The exploration, pre-commercial and commercial phase are analysed by a probabilistic approach based on the results from geological concept, dynamic simulation and risks evaluation. Considering available data and uncertainties, commercial case is built on an estimated capacity range from 2 Mt to 35 Mt; with 1 or 2 injector wells; injection rate per well between 0.25 and 0.5 CO_2 Mt/year, and injection facilities aligned with total volumes handled (with a maximum of 1 Mt per year). It is assumed that CO_2 will be transported in dense phase to the injection facilities. All monitoring infrastructure implemented during the pilot will be expanded at this stage and adapted a total injected volume, including at least one observation well, and seismic, pressure and environmental monitoring. Finally, once the usable storage capacity is exhausted, the well(s) will be safely abandoned and the site will enter a long-term post-closure monitoring phase (decades) to confirm the permanent stability of the stored CO_2 in accordance with applicable regulations. As based case, the commercial configuration will rely on two injection wells operating in parallel on the order of 15 Mt of CO_2 over 30 years and 0.5 CO_2 Mt/year injection rate per well. To continuously transport half a million tonnes of CO_2 per year, a dedicated pipeline could be constructed from the capture plant to the storage site.

4.3.3.1 Capture

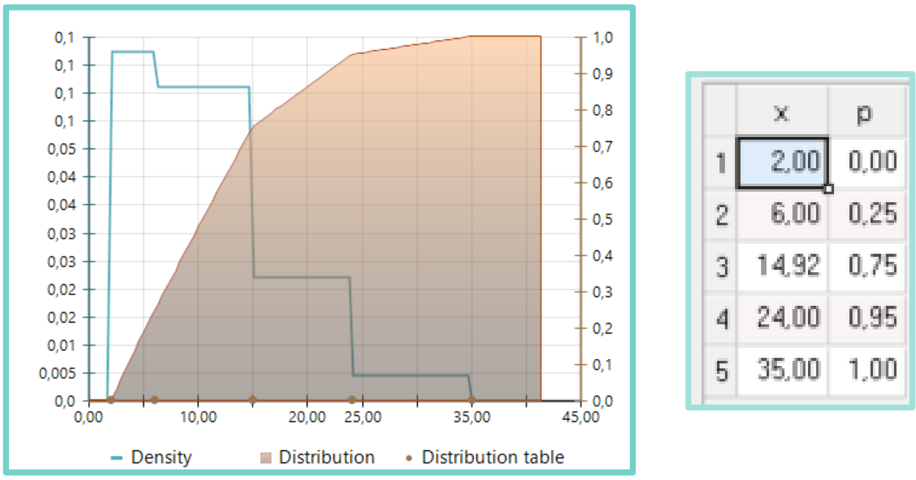
Ebro basin case doesn´t include capture source or analyse capture possibilities and costs. The CO_2 is assumed from a local industrial source (there are several candidate emitters in the region in a 60 km radius) and, for all of them, there are developed captured technologies to be applied. Costs, design and CO_2 quality is assumed on the standards.

4.3.3.2 Transport

Ebro basin case doesn´t include transport infrastructure analyse and costs. For a viability verification, it is assumed that transport to the site during pilot phase is done by liquefied CO_2 tanker trucks (each truck carries approximately 20–25 tonnes, and 3–4 trips per day are to meet the injection rate of ~30–35 kt/year). This solution is flexible, low-cost, and suitable for small volumes. In the commercial phase, a dedicated pipeline of between 14 and 30 km is therefore envisaged, designed to operate continuously and transport CO_2 in a supercritical state. This solution ensures efficiency, safety, and scalability, although it requires high upfront investment and detailed planning.

4.3.3.3 Storage

Based on the geological model analysis, dynamic simulation and risk analysis, a r*ange of estimated capacity in Lopin structure between 2 Mt and 35 Mt is defined, and injection profiles and storage site management have been selected accordingly ensuring safe operation (injection rate limited by maximum reservoir pressure). For the probabilistic approach, the distribution of estimated capacity is defined as follow:*



	x	p
1	2,00	0,00
2	6,00	0,25
3	14,92	0,75
4	24,00	0,95
5	35,00	1,00

Figure 4.9: Estimated capacity distribution and cumulative distribution for Lopin structure.

The capacity range compiles the potential compartmentalization of the reservoir (limited to 7 Mt); the base case studied and 3D simulated dynamically (covering between 7 and 15 Mt); and the optimistic case of no-compartmentalization and evaluated by 1D risk modelling (until 35 Mt). Maximum reservoir pressure and injection profile have been defined specifically for each of those ranges and referred in this text as Case 1, Case 2 and Case 3, respectively (Table 4.8).

As an example, for the 14.9 million tonnes case, operation site covers 30 years through two wells. The design considers either simultaneous or alternating injection, with rates of approximately ~0.25 Mt/year per well. Updated dynamic models confirm that the reservoir can accommodate this volume without exceeding the fracture gradient (~0.17 bar/m). The maximum predicted overpressure is 60–70 bar in the worst case, with adaptive management in place to avoid interference between wells. The CO_2 plume extends to a radius of up to 2.5–3 km per well, covering up to 15 km^2. In the long term, CO_2 is immobilized through dissolution and residual trapping. A post-injection monitoring period of at least 20–30 years is envisaged, in accordance with the European Geological Storage Directive.

The monitoring system is expanded to include a network of observation wells, periodic 3D seismic surveys, downhole sensors, DAS, InSAR, and geochemical monitoring. The integrity of legacy wells is also assessed, and a local seismic network is installed to detect induced microseismicity.

CASE	Estimated capacity (Mt)	Injector wells (units)	Well Injection rate pilot (3 years)	Well Injection rate commercial
Case 1	[2, 7)	1	0.03 MTPA	0.25 MTPA
Case 2	[7,15)	2	0.03 MTPA	0.25 MTPA
Case 3	[15, 35]	2	0.03 MTPA	0.50 MTPA

Table 4.8 Scenario for the Ebro Basin CO_2 project

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

The duration of the commercial phase depends on the estimated capacity. Injection profile for the 5Mt, 14.9 Mt and 25 Mt are presented Fig 4.10.

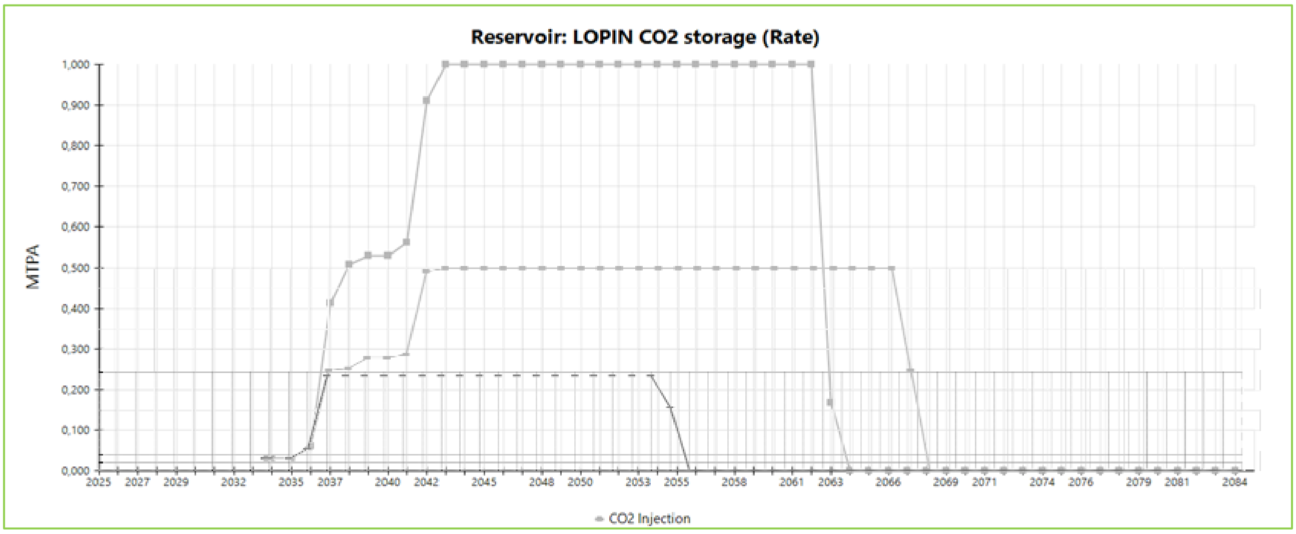


Figure 4.10: CO2 Injection profiles proposed for 5 Mt (1 well, 0.25 MTPA plateau), 14.9 Mt (2 wells, 0.5 MTPA plateau), and 25 Mt (2 wells, 1 MTPA plateau) of estimated capacity for the full life cycle.

For the probabilistic analysis of Ebro Basin case, costs (CAPEX, OPEX, ABEX), construction times, dependencies and expected success (Pg, Pp) have been defined. Parameters and distributions are shown on the Fig 4.11.

4.3.3.4 Monitoring Plan (MMV)

The Ebro Basin project establishes a comprehensive Monitoring, Measurement, and Verification (MMV) program to ensure safe CO_2 injection and long-term containment. A robust baseline is collected before operations, including 3D seismic data and groundwater samples. The injection well will be instrumented with permanent sensors—fiber-optic cables (for DAS, temperature, and pressure) and downhole tools—enabling real-time tracking of bottom-hole conditions, seismicity, and plume evolution through repeated VSP surveys. The Ebro Basin monitoring plan combines direct monitoring of the well, the subsurface, and the surface environment, using state-of-the-art technologies in line with project recommendations. Collected data will be continuously analysed and compared with model predictions. Clear alert thresholds and corrective actions are defined ensuring safe storage operations. This approach will enable field validation of reservoir behaviour and ensure effective CO_2 containment, providing the confidence needed before scaling up the project to the commercial phase.

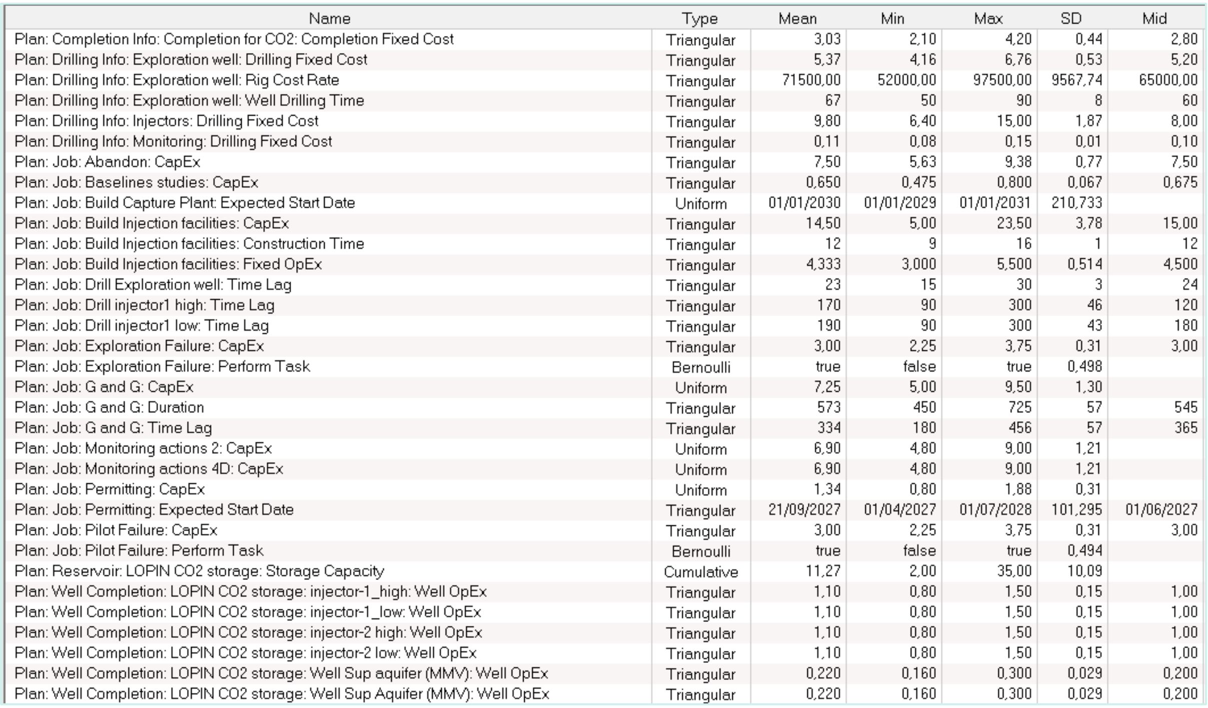
Baseline definition will be established prior to injection. This includes the acquisition of reference seismic data (e.g. 3D seismic) and groundwater/subsurface samples. In addition, the injection well will be equipped with fiber optics along the tubing and downhole instrumentation.

Pressure management is central to the plan. Continuous wellhead and bottom-hole pressure monitoring will be compared to predefined thresholds set at 90% of the estimated fracture pressure. Exceeding these limits triggers operational responses such as reducing injection rates or temporarily halting injection. Because of nearby faults, a microseismic monitoring network (fiber optics, downhole geophones, or surface seismometers) will detect small-magnitude events, with an operational limit (e.g., M > 2.0) requiring immediate suspension.

Well integrity is verified through cement bond logs after drilling and maintained via periodic tests during injection—valve checks, annulus pressure tests, and corrosion monitoring. A final integrity log is planned before abandonment.

CO_2 plume monitoring relies primarily on fiber-optic VSP, considered sufficient given the expected limited migration radius (< ~2 km). Surface 4D seismic may be added if needed. This approach aligns with strategies used in previous pilots.

Environmental monitoring includes baseline and periodic sampling of groundwater, soil, and near-surface air, along with CO_2 sensors around the site. Although leakage risk is low due to the Triassic caprock, these measures provide additional assurance. Satellite InSAR may be used to detect subtle ground deformation.



Name	Type	Mean	Min	Max	SD	Mid
Plan: Completion Info: Completion for CO2: Completion Fixed Cost	Triangular	3,03	2,10	4,20	0,44	2,80
Plan: Drilling Info: Exploration well: Drilling Fixed Cost	Triangular	5,37	4,16	6,76	0,53	5,20
Plan: Drilling Info: Exploration well: Rig Cost Rate	Triangular	71500,00	52000,00	97500,00	9567,74	65000,00
Plan: Drilling Info: Exploration well: Well Drilling Time	Triangular	67	50	90	8	60
Plan: Drilling Info: Injectors: Drilling Fixed Cost	Triangular	9,80	6,40	15,00	1,87	8,00
Plan: Drilling Info: Monitoring: Drilling Fixed Cost	Triangular	0,11	0,08	0,15	0,01	0,10
Plan: Job: Abandon: CapEx	Triangular	7,50	5,63	9,38	0,77	7,50
Plan: Job: Baselines studies: CapEx	Triangular	0,650	0,475	0,800	0,067	0,675
Plan: Job: Build Capture Plant: Expected Start Date	Uniform	01/01/2030	01/01/2029	01/01/2031	210,733	
Plan: Job: Build Injection facilities: CapEx	Triangular	14,50	5,00	23,50	3,78	15,00
Plan: Job: Build Injection facilities: Construction Time	Triangular	12	9	16	1	12
Plan: Job: Build Injection facilities: Fixed OpEx	Triangular	4,333	3,000	5,500	0,514	4,500
Plan: Job: Drill Exploration well: Time Lag	Triangular	23	15	30	3	24
Plan: Job: Drill injector1 high: Time Lag	Triangular	170	90	300	46	120
Plan: Job: Drill injector1 low: Time Lag	Triangular	190	90	300	43	180
Plan: Job: Exploration Failure: CapEx	Triangular	3,00	2,25	3,75	0,31	3,00
Plan: Job: Exploration Failure: Perform Task	Bernoulli	true	false	true	0,498	
Plan: Job: G and G: CapEx	Uniform	7,25	5,00	9,50	1,30	
Plan: Job: G and G: Duration	Triangular	573	450	725	57	545
Plan: Job: G and G: Time Lag	Triangular	334	180	456	57	365
Plan: Job: Monitoring actions 2: CapEx	Uniform	6,90	4,80	9,00	1,21	
Plan: Job: Monitoring actions 4D: CapEx	Uniform	6,90	4,80	9,00	1,21	
Plan: Job: Permitting: CapEx	Uniform	1,34	0,80	1,88	0,31	
Plan: Job: Permitting: Expected Start Date	Triangular	21/09/2027	01/04/2027	01/07/2028	101,295	01/06/2027
Plan: Job: Pilot Failure: CapEx	Triangular	3,00	2,25	3,75	0,31	3,00
Plan: Job: Pilot Failure: Perform Task	Bernoulli	true	false	true	0,494	
Plan: Reservoir: LOPIN CO2 storage: Storage Capacity	Cumulative	11,27	2,00	35,00	10,09	
Plan: Well Completion: LOPIN CO2 storage: injector-1_high: Well OpEx	Triangular	1,10	0,80	1,50	0,15	1,00
Plan: Well Completion: LOPIN CO2 storage: injector-1_low: Well OpEx	Triangular	1,10	0,80	1,50	0,15	1,00
Plan: Well Completion: LOPIN CO2 storage: injector-2 high: Well OpEx	Triangular	1,10	0,80	1,50	0,15	1,00
Plan: Well Completion: LOPIN CO2 storage: injector-2 low: Well OpEx	Triangular	1,10	0,80	1,50	0,15	1,00
Plan: Well Completion: LOPIN CO2 storage: Well Sup aquifer (MMV): Well OpEx	Triangular	0,220	0,160	0,300	0,029	0,200
Plan: Well Completion: LOPIN CO2 storage: Well Sup Aquifer (MMV): Well OpEx	Triangular	0,220	0,160	0,300	0,029	0,200

Figure 4.11: Defined distribution for selected CAPEX, OPEX and construction time

4.3.4 Proposed planning

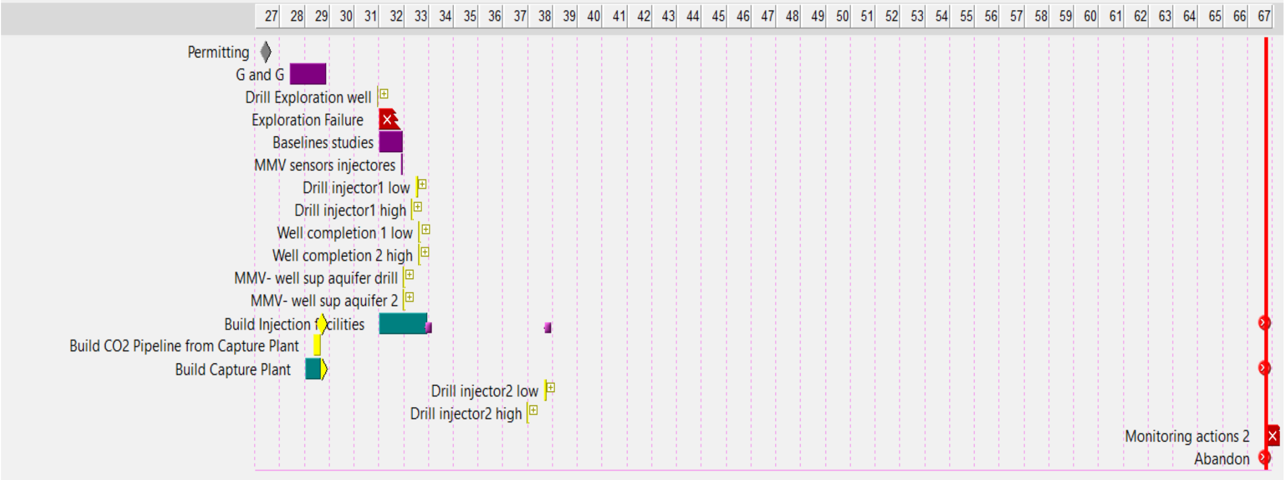
The project roadmap in the Ebro Basin has been conceived in a phased manner, starting with exploration phase, a demonstration pilot and, if successful, evolving towards a larger-scale commercial deployment. Key activities duration has been defined on a time range to evaluate the impact of potential delays in the ongoing activities- that is the case of exploration permitting grant, seismic surveys, injection facilities building, or drilling delays.

The planned phases are described below, including their estimated durations, key activities, and logistical and regulatory considerations:

- **Exploration and Characterization Phase (between 4 and 6 years):**

The project starts on 2027 with the exploration permit request and obtained between 12 and 18 months later. The exploration phase starts with detailed subsurface studies. The plan includes the acquisition of new high-resolution reflection seismic data in the Lopín area, as well as laboratory-based geochemical and geomechanical studies (Lachen et al., 2025). A critical milestone will be the drilling of an exploratory well at the proposed site and injection tests. During this phase, key data from the storage formation (porosity, permeability, initial pressure, thickness) and from the caprock will be collected, thereby reducing uncertainties in the geological model. In parallel, regulatory procedures will be initiated, including the environmental impact assessment of the pilot project, consultations with authorities and local communities (e.g. to ensure social acceptance), and the preparation of the application for a temporary storage permit for the pilot (Canteli et al., 2025b). It should be noted that no specific industrial emitter has yet been selected as a CO_2 source; therefore, negotiations for CO_2 supply for the pilot (e.g. potential agreements with regional cement or chemical plants) will also take place during this stage.

Figure 4.12: Activities schedule for the full life cycle evaluation



- **Pilot Injection Phase (3 years):**

Once site characterization has been satisfactorily completed and new data validates the geological viability in Lopin structure, and pilot (research) exploitation permits is requested and obtained, the design and construction of pilot facilities will begin. The baseline data activity is carried out during at least 1 year. A new injector well is drilled and completed (installation of injection tubing, wellhead with safety valves, and flowlines), as well as the deployment of the required surface infrastructure, including compression unit and injection plant, power supply systems, tanks and connecting pipelines, and surface monitoring equipment (Lachen et al., 2025, D4.5). During this phase, a total volume on the order of 100,000 tonnes of compressed CO_2 is expected to be injected into the reservoir over approximately three years of pilot operation. The purpose of this pilot is twofold: to demonstrate technical feasibility (injectivity and storage capacity) and to collect real-field data to calibrate the models. According to updated dynamic simulations, the CCS-1 (pilot) well could inject approximately 0.03–0.05 Mt/year without exceeding safe pressure limits, corresponding to ~0.1 Mt over three years, while respecting the operational cap (≈90 bar of overpressure) defined by caprock integrity (Ron et al., 2026). During this phase, the MMV plan will be fully implemented, with real-time monitoring of reservoir response. It is important to note that, to supply this pilot injection, the logistics plan transporting CO_2 by cryogenic tanker trucks from a nearby emitting source to the well site, given the relatively low volumes and manageable distances. This flexible solution allows pilot operations to commence without the need for long-distance dedicated transport infrastructure.

- **Intermediate Evaluation and Decision-Making (after pilot period):**

Following completion of the pilot injection (3 years), the project enters a period of comprehensive results analysis. Technical teams will compare observed data (reservoir pressures, CO_2 plume migration, microseismic events, etc.) with prior predictions. If storage performance is favourable—i.e. confirming good injectivity, absence of leakage, and controlled seismicity—the project will move forward to plan commercial-scale expansion. This will involve preparation of a Final Investment Decision (FID) report consolidating pilot learnings, an updated economic and financial assessment (Canteli et al., 2025b, D4.9), and a detailed plan for the next phase. At this intermediate stage, the geological storage concession at commercial scale will also be pursued, requiring expansion or adaptation of existing permits to cover larger volumes and longer injection periods (likely including a new Environmental Impact Declaration for the 30-year industrial phase). Based on similar experiences, a timeframe of approximately two years is estimated to secure authorizations and financing for the commercial phase following the pilot. During this period, the pilot well may remain under observation (with no further CO_2 injection), while continuing early post-injection monitoring to extend the pressure fall-off and plume evolution datasets.

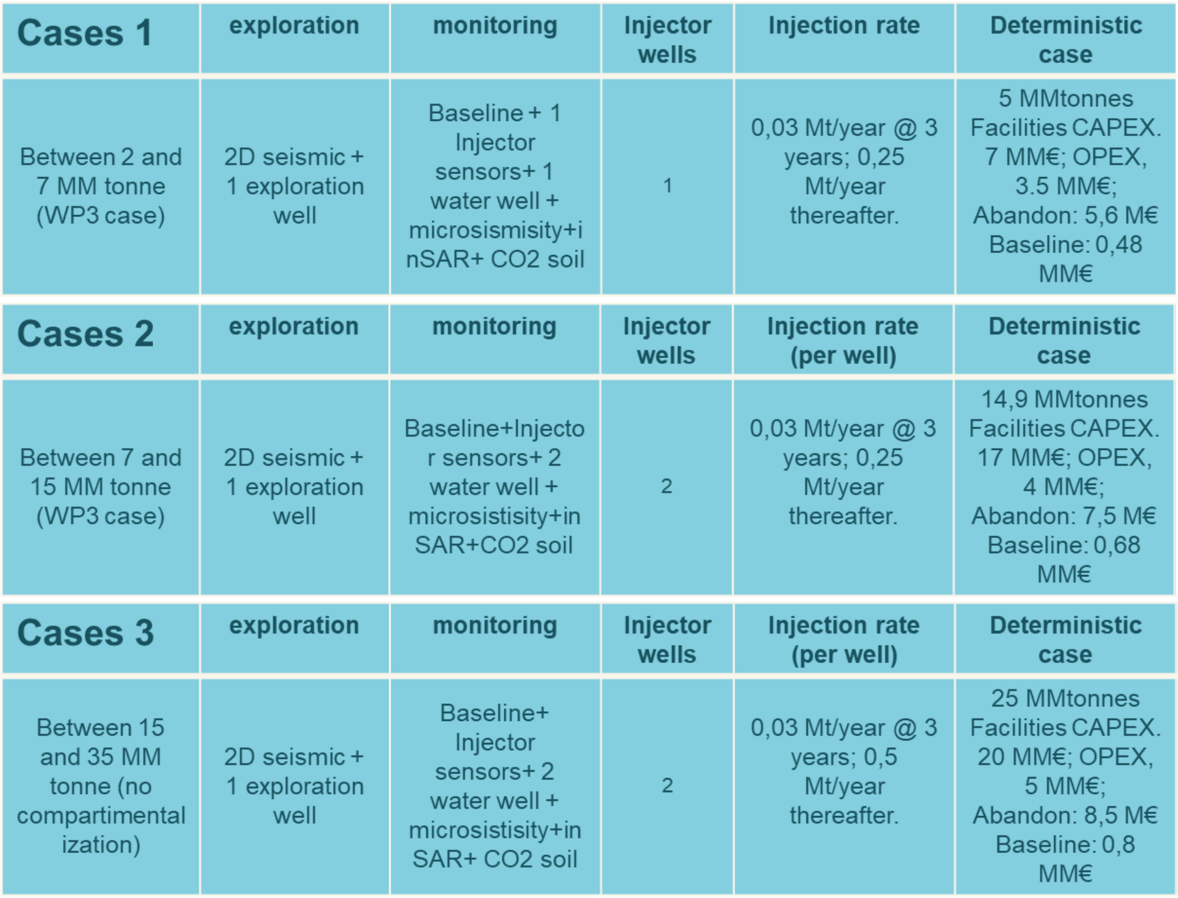
For the probabilistic approach and based on the team expert evaluation, a chance of exploration success (i.e. the probability of obtaining positive results during exploration phase and going ahead with the pilot construction) and a chance of pilot success (i.e. the probability of verifying appropriated storage complex behaviour during pilot tests) have been considered as it is indicated in Table 4.9. for (1) assuming geological and pilot success; (2) including geological chance of success and corresponding percentage of abandoned developments after exploration well results; and (3) including geological change of success and, for those who passes to pilot development, applied Pp as a percentage of no abandoned cases after analysing pilot behaviour results.

Probabilistic case studied	Pg	Pp
(1) Success case	1	1
(2) Geological success impact	0.6	1
(3) Geological and pilot success impact	0.54	0.46

Table 4.9 Geological success probability (Pg) and pilot success probability (Pp) values considered for the 3 probabilistic scenarios analysed.

- **Large-Scale Commercial Phase (until abandonment):**

Once the decision to scale up the project is taken, the plan foresees the deployment of one or two injection wells, along with an expansion of surface facilities. Commercial development is defined on the estimated capacity bases, as well as required MMV plan.



Cases 1	exploration	monitoring	Injector wells	Injection rate	Deterministic case
Between 2 and 7 MM tonne (WP3 case)	2D seismic + 1 exploration well	Baseline + 1 Injector sensors+ 1 water well + microsismisity+inSAR+ CO2 soil	1	0,03 Mt/year @ 3 years; 0,25 Mt/year thereafter.	5 MMtonnes Facilities CAPEX. 7 MM€; OPEX, 3.5 MM€; Abandon: 5,6 M€ Baseline: 0,48 MM€

Cases 2	exploration	monitoring	Injector wells	Injection rate (per well)	Deterministic case
Between 7 and 15 MM tonne (WP3 case)	2D seismic + 1 exploration well	Baseline+Injector sensors+ 2 water well + microsistisity+inSAR+CO2 soil	2	0,03 Mt/year @ 3 years; 0,25 Mt/year thereafter.	14,9 MMtonnes Facilities CAPEX. 17 MM€; OPEX, 4 MM€; Abandon: 7,5 M€ Baseline: 0,68 MM€

Cases 3	exploration	monitoring	Injector wells	Injection rate (per well)	Deterministic case
Between 15 and 35 MM tonne (no compartimentalization)	2D seismic + 1 exploration well	Baseline+ Injector sensors+ 2 water well + microsistisity+inSAR+ CO2 soil	2	0,03 Mt/year @ 3 years; 0,5 Mt/year thereafter.	25 MMtonnes Facilities CAPEX. 20 MM€; OPEX, 5 MM€; Abandon: 8,5 M€ Baseline: 0,8 MM€

Figure 4.13: Cases description for 5 Mt, 14.9 Mt and 25 Mt estimated capacity of Lopin for the deterministic evaluation

4.3.5 Economic assessment

The economic assessment of Ebro basin case has followed both deterministic and probabilistic approach using PetroVR software and based on:

- Definition of estimated capacity distribution, based on geological uncertainties and possibility of compartmentalization. A range between 2 Mt and 35 Mt has been considered with P75= 14.9 Mt. The deterministic evaluation is based on 5 Mt, 14.9 Mt and 25 Mt.
- Definition of exploration phase: geological and geophysical campaigns, and exploration well and test.
- Definition of injector well(s) and injection profiles, for pilot phase (1 well, 0.03 MTPA for 3 years) and for commercial phase (table XX). Well costs including drilling and completion).
- Definition of the injection facilities: capture plant and transport are out of the study. Surface facilities (reception, compressor and injectors) are defined based on maximum handled CO_2 volumes.
- Schedule (or planning): the different activities carried out in time, considering dependency between activities. Uncertainty (delays, advances) are included for key activities (permitting process, drilling time, facilities building) by required time distribution. The considered activities are exploration permit application and granting, exploration phase, baseline measurements, drill and completion wells, injection facilities construction, MMV plan application, and abandonment when the 95% of total estimated capacity is reached.

- Chance of geological success (Pg) and chance of exploitation success (Pe): for the probabilistic approach, a chance of geological success Pg=0.6% is applied (i.e. after exploration well, 60% of cases pass to next phase and 40% the project is abandoned); and after pilot phase, a change of exploitation success of Pe=0.54% is applied (i.e. after 3 years of pilot operation, 54% of cases pass to commercial phase and 36% project is abandoned). Pg and Pe have been defined bases on existing information and internal experts panel definition.
- Economic model: It is based on an economic cashflow model, where it is assumed that revenues correspond to the value of tonnes of CO_2 stored per year at the EU ETS price.
- Price forecasts (base, low and high) have been assumed. Other financial parameters of interest are discount rate (9%) and inflation (2.2%). Results are discounted to 2025.

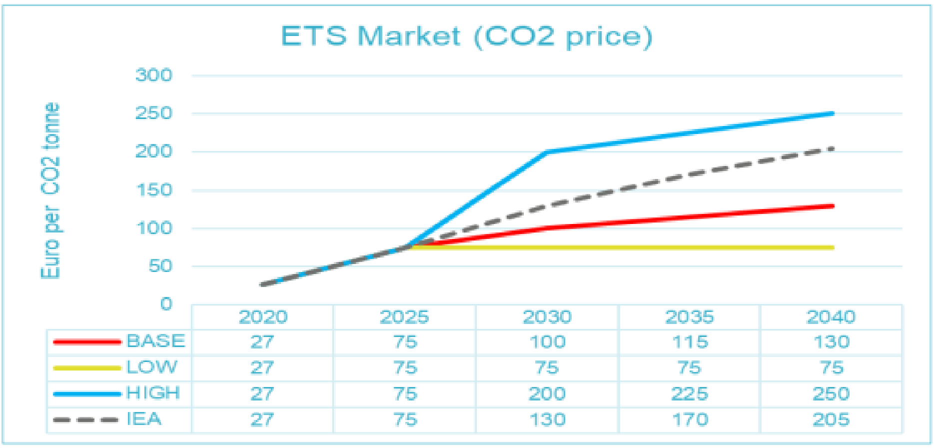


Figure 4.14: CO2 ETS forecast prices (Base, High and Low)

- Costs (CAPEX and OPEX) have been defined as Class IV at 2025 and, for distribution definition, considered triangular distribution with real cost 2025 as centre point (-20%, +30%).
- Deterministic results: they are indicated for an estimated capacity of 5 Mt, 14.9 Mt; and 25 Mt.
- Probabilistic results: Monte Carlo with 10,000 simulations/5000 for comparative criteria.
- Sensitivity analysis has been made to the distributions of the capacity; a percent to be received per tonne (storage fee).

The **deterministic results** for 5 Mt, 14.9 Mt and 25 Mt for the 3 defined prices forecasts show positive values for NPV (2025, 9%) for all cases assuming CO_2 ETS price for 1 tonne of CO_2 injected, with investments between 65 M€ and 105 M€, and max cashflow between 37 M€ and 64 M€ depending on storage capacity considered. However, the breakeven of the CO_2 price for the 3 deterministic cases have been also calculated giving a 73 €/tonne if 5 Mt of estimated capacity; 42 €/tonne if 14.9 Mt of estimated capacity, and 27 €/tonne if 25 Mt of estimated capacity. Total investment for the storage site development (pilot and commercial development) is estimated between 65 M€ and 105 M€ (2025 prices). (Table 4.10).

Case	CAPEX (Million€)	OPEX (Million€)	Max Cash out (Million€)	NPV (9, 2025, BP) (Million€)	NPV (9, 2025, LP) (Million€)	NPV (9, 2025, HP) (Million€)	Breakeven (€/tonne)
5 Mt	65	135	-37	82	16	165	73

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

14,9 Mt	99	275	-49	178	51	337	42
25 Mt	105	280	-64	382	143	690	27

Table 4.10 Deterministic results for 5 Mt, 14.9 Mt and 25 Mt estimated capacity

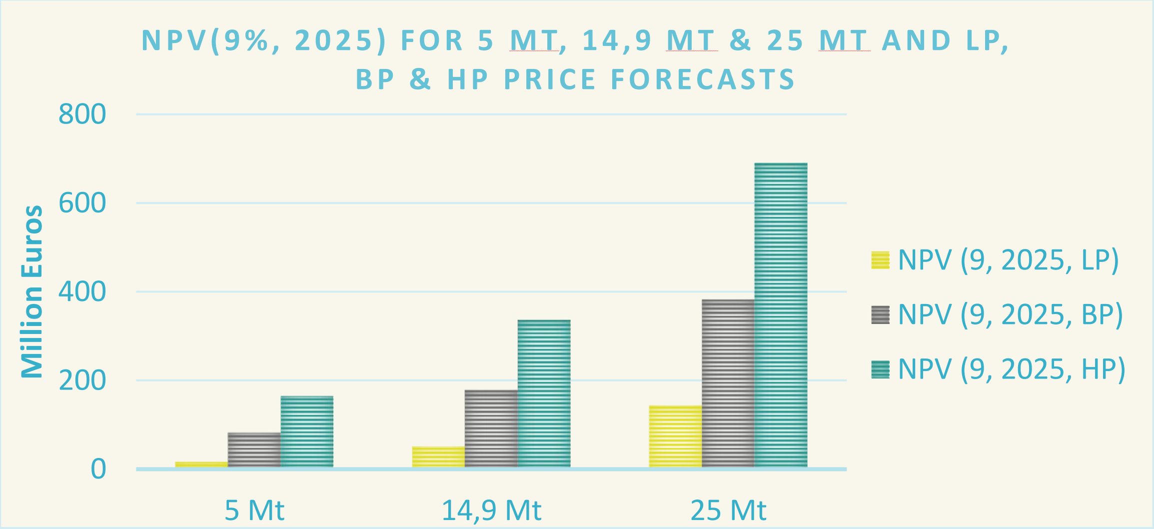


Figure 4.15: NPV (9%, 2025) for 5 Mt, 14.9 Mt and 25 Mt deterministic cases

Based on the **probabilistic analysis**, the cases have been analysed: (1) Considering success case (i.e. Pg=1 and Pp=1); (2) considering Pg=0.6 and Pp=1; and (2) considering Pg=0.54 & Pg=0.46. All cases have been analysed for the full life cycle and defining parameters distributions for key elements in CAPEX, OPEX and timing (table 4.11). Results are shown on Table 4.11, Table 4.12 and 4.13, respectively.

In the first case (1) in which all starting evaluations go throw exploration, pilot and commercial phase, results on NPV for all considered prices are positive (except the very low tale of the low price, <P10) giving very good overview of a solid case. However, it should be considered that the assumption of giving ETS price per tonne storage it is just for a common reference and, for a business case evaluation, the ETS price per tonne should cover capture, transport and storage phases.

Singles (Pg=1; Pe=1)	Unit	Mean	P10	P50	P90	Min	Max
Abandonment Year BP		2058	2051	2057	2065	2044	2073
Abandonment Year HP		2058	2051	2057	2065	2044	2073
Abandonment Year LP		2058	2051	2058	2064	2044	2073
Results: NPV 9- BP	M€	168	59	144	327	25	428
Results: NPV 9- HP	M€	319	128	283	592	66	773
Results: NPV 9- LP	M€	47	2	32	122	-11	165
Volumes: Total CO2 injected	Million tonnes	11	4	10	17	2	33

Table 4.11 NPV (9%, 2025) and abandonment year results for the 3 CO2 prices forecast (BP, LP, HP) and success case (Pg=1 & Pp=1) based on probabilistic analysis.

In the second case (2), the probabilistic economic results for the full life cycle and based on base price evaluating the geological success (Pg=0.6 & Pp=1), the cumulative distribution shows a P50 of 70 MM€ (mean value of 94 M€) with negative values in the low side of the distribution (P<15%). Similar results are obtained high price case although, for Low Price case, it is a 48% chance of negative NPV (table 4.10). In conclusion, only for the low tale (<p20) values for the 3 considered prices are negative giving, again, a very positive results and with the same ETS price assumption mentioned before.

Table 4.122 NPV (9%, 2025) and abandonment year results for the 3 CO2 prices forecast (BP, LP, HP) and Pg=0.6 & Pp=1 based on probabilistic analysis.

Singles	Unit	Mean	P10	P50	P90	Min	Max
Abandonment Year_BP		2048	2032	2054	2064	2031	2073
Abandonment Year_HP		2048	2032	2054	2064	2031	2073
Abandonment Year_LP		2048	2032	2053	2063	2031	2073
NPV 9- BP	€M	94	-17	70	311	-20	426
NPV 9- HP	€M	183	-24	150	562	-29	764
NPV 9- LP	€M	22	-17	5	113	-20	167
Total CO2 injected	M tonne	6	2	5	16	2	33
First injection date		02/07/2033	01/01/2032	25/10/2033	28/09/2034	30/10/2030	30/01/2036

It has been also analysed the impact of first injection date (delays and fast-tracks permits, construction, deliveries, …). If the deterministic cases define the expected first injection date at 2033, considering the impact of different events it can be expected a 6-year range, with an estimated impact of a 10% reduction of NPV value for 1 year delay only due to permitting process. (Fig. 4.16)

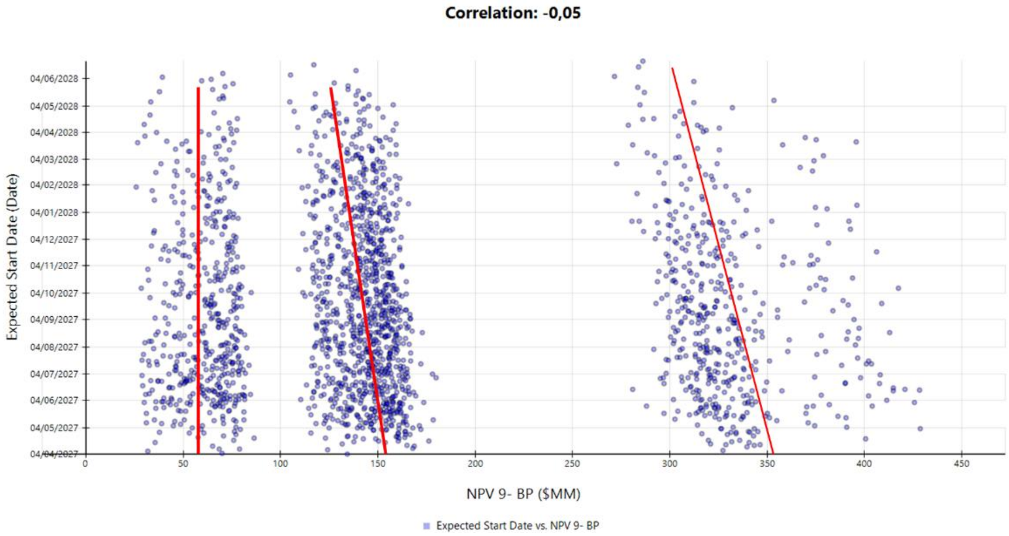


Figure 4.16: Impact on permitting delay on NPV (9%, 2025)

Finally, the results considering both Pg=0.54 and Pe=0.46 (3) bring more clarity about the impact of geological and operative uncertainties, respectively. These probabilities have been obtained by an internal expert evaluation. In that case, with this combined failure cases, for all forecast prices results are negative for <P50- however, the expected risky results in at least 50% of the cases and for the 3 forecast prices are very high (NPV (9%, 2025,BP)>300 Million Euros) with could be considered a good results for thinking about next step.

Table 4.13 NPV(9%, 2025) and abandonment year results for the 3 CO2 prices forecast (BP, LP, HP) and Pg=0.54 & Pp=0.46

Pg=0.54; Pe=0.42	Unit	Mean	P10	P50	P90	Min	Max
Abandonment Year_BP		2039	2030	2036	2059	2030	2072
Abandonment Year_HP		2039	2030	2033	2059	2030	2072
Abandonment Year_LP		2039	2030	2034	2059	2030	2071
NPV 9- BP	M€	36	-21	-16	185	-25	463
NPV 9- HP	M€	76	-26	-8	331	-32	796
NPV 9- LP	M€	10	-23	-6	68	-27	207
Total CO2 injected	Mtonne	3	0	5	16	0	33

based on probabilistic analysis.

4.3.6 Social and environmental assessment

Lopín should be understood as a case of conditional social acceptance, not of clear support or clear rejection. Evidence from the Ebro Basin shows that acceptance would depend above all on whether the project is perceived as safe, territorially fair, transparent and beneficial for the host area. A central issue is that Lopín is far from major CO_2 emitters – far in the sense that no direct benefits are perceived in these areas- , which immediately raises concerns about territorial justice: local communities may question why a sparsely populated rural area should assume the risks and burdens of storing emissions produced elsewhere. In this context, the project is assessed through a pragmatic cost-benefit logic in which the promise of local development must clearly outweigh the perceived risks and the area's historical distrust toward externally driven energy projects.

The main concerns identified for Lopín relate to possible leakage, aquifer contamination, induced seismicity, transport-related risks, environmental and agricultural impacts, and the overall cost and long-term credibility of the project. These concerns are reinforced by the perception that CCS could become an excuse to delay deeper emissions reductions and by the fear that the area could become an "experimental village" for non-local CO_2. At the same time, residents and stakeholders do identify potential benefits, especially job creation, population retention, infrastructure improvements, fiscal returns, attraction of companies and broader economic revitalisation. However, these expected benefits are not taken for granted: they are treated as credible only if they are specific, visible, verifiable and fairly distributed.

A recurrent finding is that information, transparency and early engagement are not secondary communication tasks but enabling conditions for project legitimacy. Because familiarity with CCS has been low, early-stage engagement offers an opportunity to shape perceptions before positions harden, but only if the process is seen as genuine rather than merely consultative. Across the Spanish activities, participants demanded continuous information, accessible technical explanations, transparency regarding permits, inspections, profit-sharing and risks, and mechanisms for local oversight, including citizen committees, independent audits and, in some cases, veto or strong local participation rights. Declared transparency without citizen voice was not regarded as credible.

This also points to potential risks of local contestation. Opposition could intensify if the project is perceived as imposed from outside, if the permitting process is opaque, if benefits remain vague or delayed, or if communities feel they are again being asked to host infrastructure that primarily serves external actors. Previous experiences of broken promises in renewable and infrastructure projects have created a legacy of distrust that may easily reactivate criticism unless the project includes binding guarantees, compliance clauses, sanctions for non-delivery, and independent verification. In practical terms, lack of perceived local benefits is itself a major project risk.

For project permitting, communication and design, the implication is that the Lopín concept should incorporate social requirements from the outset. This means rigorous and accessible environmental impact assessment; clear explanation of safety measures, monitoring and transport arrangements; transparent administrative and permitting processes; independent monitoring and external audits; and a concrete local benefit package linked to community priorities such as employment, training, infrastructure, public services and regional development. Communication should not rely on generic climate arguments alone, but should explain why Lopín is being considered, why CCS is justified in this case, what the local benefits are, what the limits and risks are, and how the community will retain oversight throughout the project lifecycle. In short, the viability of Lopín will depend not only on technical and economic robustness, but on whether the project can credibly demonstrate safety, fairness, transparency and tangible value for the territory.

From an enviromental point of view, the closest population centres to the area of interest are Codo, 3 km north; Belchite, 3.8 km to the west; Almonacid de la Cuba, 7.7 km to the southwest, Letux 9.4 km to the southwest; and Lécera and Vinaceite, 10 km to the south and southeast, respectively. As for the Natura 2000 Network, the closest areas are the SCI (ES2430091) "Flats and steppes of the right bank of the Ebro" and the SPA (ES0000136) "Estepas de Belchite-El Planerón-La Lomaza", both about 4 km north of the area of interest. No impact on the geological heritage is expected, with the nearest LIG (IB069. Succession of the Lower and Middle Jurassic of Belchite-Almonacid de la Cuba) more than 5 km from the project. The hydrogeological study confirms that there is no permanent natural surface water course, nor are any notable temporal courses identified. No impact on Habitats of Community Interest (HIC) is expected. According to approved EIA in the thereby area, additional measures of protection for avifauna to the *Cernícalo Primilla* (Falco naumanni) are expected. In general, environmental conditions are well studied, no environmental stoppers are identified, and preventive measures during construction and operation phase are expected and could be easily included in facilities design.

4.3.7 Risk-benefit assessment

SWOT analysis to underline the strength and weakness of the proposed project are here presented.

Strengths	**Weaknesses**
• Regional geology well-known and uniform • Proven storage structure and regional caprock • Very low natural seismicity • Unpopulated area • Regional Government with CO2 store experience • Citizens open to CCS development	• Few and old subsurface data • No seismic survey covering the area • Possible compartmentalization • Uncertainty about CO_2 source and purchase cost for the pilot
Opportunities	**Threats**
1. Develop local industry 2. Direct Air Capture potential (renewable energy) 3. Community approach 4. Proximity to regional industrial area	• Exploration license application time • Uncertainty in national CCS policy support • Uncertain access to EU/national funds for the pilot

Table 4.144 - SWOT analysis of the Ebro Basin CO_2 project

4.3.8 Conclusions

The recommendations for next step are addressed to reduce geological uncertainties, that is, seismic surveys to define in more detail potential for compartmentalization, reevaluate the pressure front by improved petrophysics features, and review estimated capacity. The impact of this information on the Pg and Pp will bring closer range for economic results and better bases for a carry-on decision.

In paralleled, it should be studied CO2 potential sources – including DAC implementation- to better understand applicable business cases.

4.4 Upper Silesia (Poland)

In contrast to the Paris, Lusitania and Ebro basins, this deliverable does not present a full pre-investment proposal for the Upper Silesia Basin. Instead, the objective is to provide a structured assessment of the technical, regulatory and economic feasibility of an onshore CO2 storage concept at the Pągów-Milanów site.

The scope is therefore focused on:

- defining a phased development scenario (pilot and potential commercial scale),
- analysing the regulatory and permitting framework applicable in Poland,
- outlining the transport and storage configuration options,
- presenting a simplified economic assessment,
- identifying key environmental, social and investment risks.

The Polish case is treated as a conceptual and pre-investment stage assessment rather than a bankable project proposal. The intention is to demonstrate technical plausibility, identify major constraints and uncertainties, and evaluate whether further development towards a full investment-ready proposal would be justified under current regulatory and market conditions.

Given the absence of operational CO_2 transport infrastructure and storage projects in Poland, the Upper Silesia case serves primarily as a system-level feasibility analysis and risk-reduction exercise, rather than an immediate deployment plan.

4.4.1 Overview and context

The proposed development path for Upper Silesia Basin concerns an onshore CO_2 storage project located in the Pągów-Milanów area within the Upper Silesia Basin, Poland. The concept is structured as a phased development including a pilot injection stage followed by potential commercial-scale deployment. The study investigates the feasibility of developing a geological CO_2 storage site in southern Poland, while no operational CO_2 storage site currently exists in Poland, and CCS remains at an early implementation stage. Upper Silesia is characterised by high industrial CO_2 emissions, dense population and long experience in subsurface operations, making it a technically relevant but socially sensitive location for onshore CCS deployment.

4.4.2 Executive summary

The proposed CO_2 storage project in the Pągów-Milanów area is based on a staged development approach comprising:

- Pilot phase: 30 kt/y, for 3 years, road transport
- Commercial phase: 300 kt/y, 25 years, pipeline transport
- Post-closure monitoring: minimum 20 years (as required by Polish Geological and Mining Law)

The project assumes CO_2 supply from industrial emitters located within approximately 30–80 km from the storage site. During the pilot phase, transport is foreseen by road (cryogenic tankers), while commercial operation assumes pipeline transport.

The selected storage structure is a saline aquifer within the Jurassic formations of the Częstochowa District. Modelling results indicate an estimated storage capacity of approx. 31 Mt, while the planned injection volume over both phases amounts to approx. 7.5 Mt.

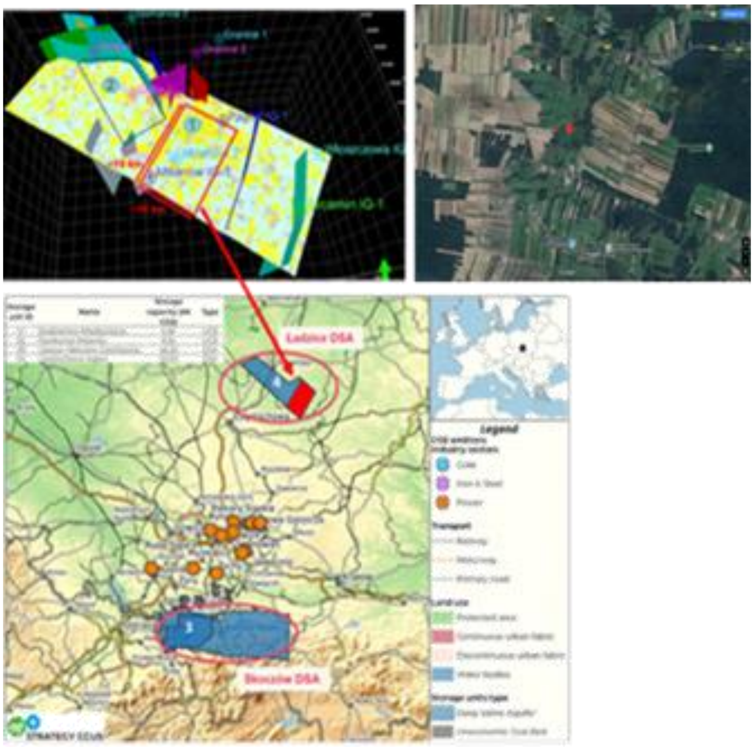


Figure 4.1717 Storage site location

The simplified economic assessment shows that:

- the pilot phase alone is not economically viable.
- full development becomes economically feasible only under high EU ETS carbon price scenarios.
- the business case is highly sensitive to carbon price evolution, capture cost and pipeline CAPEX.

The Polish regulatory framework provides legal clarity but is characterised by a multi-stage permitting process and significant pre-investment risk concentration. Social acceptance and cumulative environmental pressures in Upper Silesia represent additional challenges requiring early stakeholder engagement and transparent monitoring.

The project remains at conceptual stage and requires further geological verification, environmental assessment and financing before investment decision.

4.4.3 Proposed development

4.4.3.1 Capture

CO_2 capture is not tied to a single emitter at this stage. Potential sources include power plants, cement kilns, steelworks, chemical plants and waste-to-energy facilities located within 30–80 km of the storage site.

Capture technologies considered are dominated by post-combustion amine-based systems, reflecting the industrial structure of Upper Silesia. No detailed engineering design of capture installations has been prepared within this deliverable, however CO_2 conditioning (dehydration, compression) should be assumed to ensure compliance with Polish regulatory requirements for injected CO_2 stream quality.

In accordance with the Regulation of the Minister of Environment of 30 October 2015, concerning the detailed requirements for the operation of underground carbon dioxide storage, the following specifications apply to the CO_2 stream directed to geological storage facilities in Poland:

Capture technology	Minimum CO_2 content (%)
Post-combustion	> 99.5
Pre-combustion	> 96
Oxy-fuel combustion	> 80

Table 4.1515 Minimum CO_2 content by capture technology scenarios

Substance	Maximum concentration
Hydrogen sulfide (H_2S)	< 0.005%
Carbon monoxide (CO)	< 0.3%
Nitrogen (N_2)	< 0.2% (post-combustion), < 4% (pre-combustion), < 19% (oxy-fuel)
Nitrogen oxides (NO_x)	< 0.001% (post), < 0.002% (others)
Sulfur oxides (SO_x)	< 0.001%
Water vapor (H_2O)	< 0.0001%
Heavy metals (e.g., Hg, As)	< 0.01 ppm
Tracer substances:	
– Noble gases (e.g., Ar)	< 10 ppm
– SF_6	< 0.1 ppm
– Radiocarbon ($^{14}CO_2$)	< 0.00001 ppm

Table 4.1616 Maximum allowable impurities

Physical parameters of CO_2 (supercritical state) are:

- **Pressure**: minimum 80 bar
- **Temperature**: between –20°C and +30°C

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

These criteria ensure the compatibility of the injected CO_2 stream with geological formations, minimize corrosion risks, and support effective monitoring and containment within the underground storage complex.

4.4.3.2 Transport

The transport of carbon dioxide from the capture site to the geological storage location is a critical component of CCS (Carbon Capture and Storage) systems. For the pilot and commercial phases of the project in Upper Silesia, two transport options are considered:

- Road transport by cryogenic tankers, intended for small quantities of CO_2, mainly during the pilot phase by cryogenic tankers carrying 20–25 tonnes of liquefied CO_2 per trip. CO_2 transported in a liquid state at approximately –20°C and 17–25 bar
- Pipeline transport during commercial scale, in a dense phase (supercritical or compressed gas) at approx. 120 bar and 27°C.

Pipeline routing and corridor assessment have not been completed in this study and require dedicated feasibility studies, as well as environmental assessment.

For the pilot phase (30 kt/year), road transport offers flexibility, simplicity, and lower upfront investment. For the commercial phase (300 kt/year), pipeline transport is significantly more cost-effective, safer, and environmentally preferable.

It is recommended that the pilot infrastructure be designed in a way that facilitates a smooth transition to pipeline transport during the commercial phase.

4.4.3.3 CO_2 reception infrastructure at the injection site

The injection terminal is the final part of the CCS chain and is responsible for safely receiving compressed CO_2 delivered via pipeline or road transport, regulating and stabilizing CO_2 parameters (pressure, temperature, flow) to ensure injection quality control and operational safety. Adaptability to varying flow rates, and full integration with monitoring, reporting, and emergency response systems should be provided.

Main components of the CO_2 injection terminal:

- CO_2 receiving station – equipped in buffer tanks and gas analysers to verify CO_2 purity (e.g., H_2O, H_2S content),
- CO_2 conditioning and regulation station to adjust the physical properties of injected CO_2 (pressure and temperature of geological formation) including heat exchangers, pressure equalization systems, additional CO_2 compressors,
- safety and emergency pressure relief systems,
- injection high-pressure wellheads,
- monitoring wells,
- supporting installations such as system for real-time monitoring and remote operation, backup power supply (UPS and diesel generators), telecommunications and security systems.

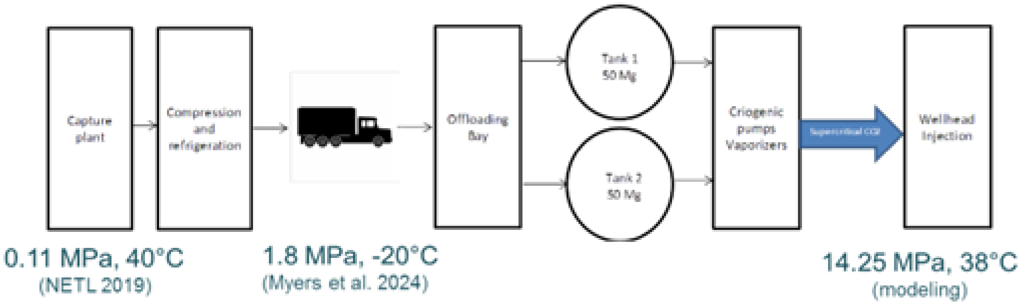


Figure 4.1818 Schematic CO_2 supply chain

4.4.3.4 Storage

The selected storage structure is located within the Pągów–Milianów area in the Jurassic formations of the Częstochowa District. As a result of the modelling performed as part of WP3, the IN-1A injection well was selected. Reservoir modelling indicates a storage capacity exceeding 31 Mt CO2, with average porosity between 14.9-19.3% and permeability ranging from 150 to 950 mD. Initial reservoir pressure is approximately 108 bar at a reference depth of 1000 m, with average temperature of 38°C. The area of the "Pągów-Milianów" deposit in Ładzice DSA - Jurassic Czestochowa District is approximately 190 km^2. Injection is planned through a single vertical well during the pilot phase, with potential adaptation to deviated wells during commercial operation. The caprock integrity and fault framework were included in the modelling assumptions.

The Łódź Basin, which encompasses the planned storage site, has been included in the Annex to the Regulation of the Minister of the Environment of September 3, 2014, on areas where underground carbon dioxide storage complexes are permitted (Journal of Laws, item 1272) (Figure 4.1719).

4.1.8 Proposed planning

The preliminary schedule (pilot and commercial phases):

- modelling and characterization of deposit (3D seismic) in the year 0
- administrative procedures to obtain authorization to undertake pilot-scale operations below 100 kt; obtaining financing
- conducting a feasibility study and finding a contractor
- infrastructure construction for injection and monitoring, drilling and completion of the well
- injection at a pilot scale and monitoring
- after proving technical viability of the technology, making a decision to continue the project on a commercial scale
- during the pilot phase, initiation of the procedure aimed at obtaining permission to continue the project on a commercial scale
- during the pilot phase, commencement of pipeline design, permitting and construction
- injection on the commercial scale for 25 years
- monitoring for 20 years after closing of the well

Key uncertainties:

- Time for permissions
- Time for FID decision after pilot
- Source of financing the pipeline (who should invest?)

- EUA prices

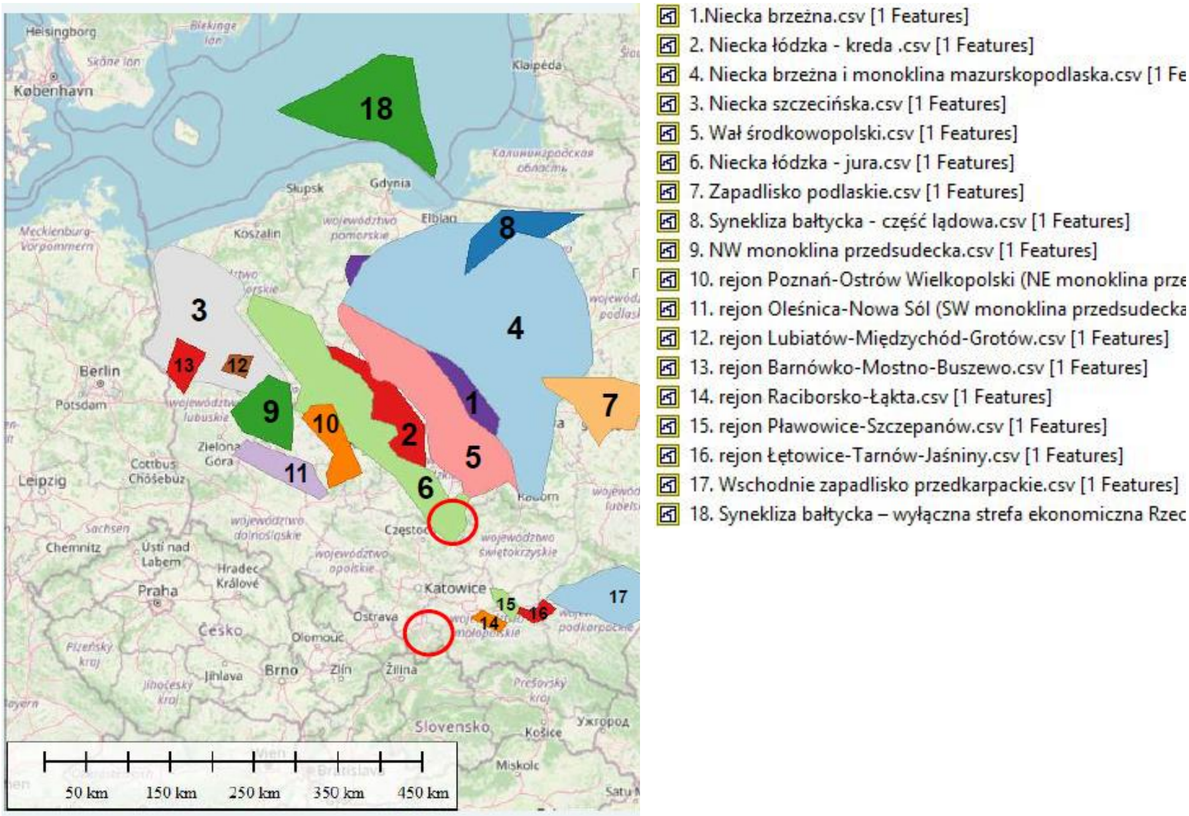


Figure 4.19 Considered storage locations

Phase	Pilot	Commercial
Amount of CO_2	30 kt/y	300 kt/y
Transport	road 4 trucks *25 t/d=100 t/d * 300 d = 30 kt/y	road/pipeline
Duration	3 years of injection	25 years of injection
Total amount of CO_2		7.5 Mt

Table 4.1717 Comparison of assumptions for pilot and commercial phase

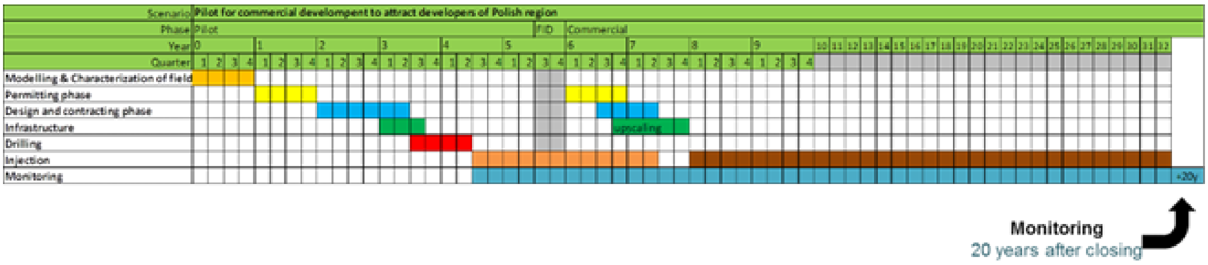


Figure 4.2020 Foreseen timeline for Upper Silesia project

4.4.4 Economic assessment

Investment expenditures (CAPEX) were estimated based on the results of the work carried out within the STRATEGY CCUS project and available literature data. Due to the very low level of investment advancement (study phase), a contingency of 20% of CAPEX was included in the calculations. For the purpose of calculating economic efficiency indicators, OPEX components were adjusted for the inflation rate. To assess the economic efficiency of the analysed concept of CO_2 capture, transport and injection into the underground reservoir, the NPV and IRR indices were calculated for three scenarios of forecast prices of CO_2 emission allowances purchase:

- Scenario 1 - base CO_2 price,
- Scenario 2 - low CO_2 price,
- Scenario 3 - high CO_2 price.

Separate calculations were made for the pilot phase of CO_2 injection and separate calculations covering the pilot phase, the commercial phase and the 20-year monitoring period after the completion of CO_2 injection.

PILOT PHASE						
Scenario	**CAPEX**		**OPEX**		**NPV**	**IRR**
	M€	€/t CO_2	M€	€/t CO_2	M€	%
Scenario 1 - base CO_2 price	21.07	234.13	26.31	292.32	-27.28	non-existent
Scenario 2 - low CO_2 price					-28.73	non-existent
Scenario 3 - high CO_2 price					-21.56	non-existent
TOTAL - PILOT + COMMERCIAL PHASE + MONITORING (20 years)						
Scenario	**CAPEX**		**OPEX**		**NPV**	**IRR**
	M€	€/t CO_2	M€	€/t CO_2	M€	%
Scenario 1 - base CO_2 price	254.70	33.56	725.10	95,53	-62.67	non-existent
Scenario 2 - low CO_2 price					-142.03	non-existent
Scenario 3 - high CO_2 price					**110.10**	**16.3%**

Table 4.1818 Summary of the results of economic efficiency calculations for the scenario of CO_2 capture, transport and injection into the underground reservoir for Upper Silesia project.

Key findings:

- Pilot phase alone: negative NPV under all carbon price scenarios.
- Combined pilot + commercial phase: positive NPV only under high EU ETS price scenario.
- CAPEX dominated by pipeline construction in commercial phase.
- OPEX dominated by capture cost across the CCS chain.
- Economic feasibility highly sensitive to carbon price trajectory.

No dedicated national CCS support mechanism has been assumed.

Risks and uncertainties

- Pipeline CAPEX costs

- EUA price
- Long-term monitoring costs
- Administrative procedures

4.4.5 Social and environmental assessment

Key positive aspects:

- Emission Reduction
- CCS Competence Development
- Compliance with EU Climate Policy

Key environmental issues:

- Surface footprint and land use conflicts.
- Transport-related nuisance during pilot.
- Subsurface integrity and leakage risk perception.
- Long-term monitoring obligations.

Upper Silesia is a region with significant cumulative industrial environmental pressures, which influences public perception of new subsurface activities.

Mitigation measures include:

- Early stakeholder engagement.
- Transparent communication of monitoring results.
- Traffic management during pilot.
- Strict adherence to EIA and MMV requirements.

Hurdles: Site-specific social surveys have not yet been conducted.

4.4.6 Risk-benefit assessment

The SWOT analysis indicates that the proposed Upper Silesia CO_2 storage project is strategically well aligned with EU climate objectives. Its main challenges relate to further detailed geological characterisation of storage site, high pre-investment cost, regulatory uncertainty, and social acceptance. However, these weaknesses are counterbalanced by strong opportunities linked to EU funding mechanisms, increasing CO_2 prices, and the potential to establish the first large-scale CCS hub in Poland. A phased development approach combined with robust monitoring and stakeholder engagement is key to maximising project benefits while mitigating risks.

Strengths	**Weaknesses**
• High CO_2 emission reduction potential • Suitable reservoir conditions • Modular development concept – A gradual transition from pilot (30 kt/y) to commercial scale (300 kt/y) reduces investment and technical risk.	• Geological Data Availability – lack of detailed seismic data and well archives that would reduce modeling uncertainty and geological risk during the pilot phase. • High Cost of Pre-Investment and Pilot Phase • Dependence on EUA Prices

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• The location is included in the regulation defining areas permitted for underground carbon dioxide storage	• Lack of a Single Designated Reference Emitter – This hinders precise allocation of costs and responsibilities in the CCS chain. • No existing CO_2 infrastructure
Opportunities • Possibility of obtaining EU Financial Support • Rising EUA prices and regulatory pressure • Integration of multiple emitters – possibility of creating a regional CCS hub • Development of national competencies – the project builds know-how in the geology, monitoring, and regulation of CCS in Poland.	**Threats** • Public acceptance – concerns among local communities about CO2 safety and transport • Risk of rising CAPEX costs – particularly for pipeline infrastructure and drilling. • Long-term storage liability – legal and financial risks associated with the post-closure period may discourage investors. • Uncertainty related to carbon pricing • Delays and lengthy permitting processes

Table 4.1919 SWOT analysis for Upper Silesia project

4.5 Macedonia Basin (Greece)

4.5.1 Overview and context

The Mesohellenic Trough in West Macedonia represents a large-scale onshore CO_2 storage system with the potential to support long-term decarbonisation strategies beyond the immediate regional context. Its relevance is primarily defined by the presence of extensive deep saline formations, notably the Pentalofos and Eptachori units, which provide storage capacities exceeding 1 Gt of CO_2 and enable multi-decadal operation at regional scale [Koukouzas et al. (2023), Tyrologou et al. (2023), Tyrologou et al. (2025)].

Recent developments in the regional energy system significantly influence the role of CCS within Western Macedonia. The progressive phase-out of lignite-based power generation, combined with the planned conversion of Ptolemaida V to natural gas operation, substantially reduces the long-term availability of concentrated CO_2 emission sources in the area. As a result, the development of a CCS system based solely on local emissions becomes increasingly constrained, both in terms of scale and long-term viability [Samaras et al. (2023)].

Under these conditions, the strategic positioning of the Mesohellenic Trough shifts from a source-driven storage concept toward a storage-led system, where the availability of geological capacity becomes the primary driver of development. In this context, the basin is not defined by its ability to capture CO_2 locally, but by its capacity to receive, store and manage CO_2 from external sources, including industrial regions with limited domestic storage options.

From a technical perspective, the storage system is characterised by moderate porosity and relatively low permeability formations, implying that injectivity is controlled by pressure-driven flow rather than high-transmissivity conditions. Consequently, CO_2 injection leads to pressure buildup that propagates through hydraulically connected reservoir units, defining the operational limits of the system. This behaviour requires careful management of injection rates to maintain reservoir pressure below thresholds associated with caprock integrity and fault reactivation, while ensuring sufficient injectivity for sustained operation.

Within this framework, the presence of multiple stratigraphic units becomes a critical advantage. Storage capacity can be progressively accessed across different horizons, allowing injection to be distributed spatially and reducing localised pressure accumulation. This multi-layered configuration supports a flexible and scalable storage strategy, particularly in scenarios where CO_2 supply may vary over time due to external sourcing.

At system level, the development of the Mesohellenic Trough must therefore be considered in connection with transport infrastructure capable of linking the basin to external emission sources. While local transport distances remain relatively short, the long-term viability of the system depends on its integration within broader CO_2 transport networks, including potential cross-border connections. This introduces additional technical and economic considerations, but also significantly expands the role of the basin within the European CCS landscape.

Overall, the Mesohellenic Trough should be understood as a pressure-managed storage system with strategic relevance that extends beyond the local context. Its development is not constrained by the availability of regional emissions, but by the ability to integrate geological capacity, transport infrastructure and operational control into a coherent system. Under this perspective, the basin provides a technically credible foundation for the implementation of a large-scale CO_2 storage hub in Greece, with the potential to support wider regional decarbonisation needs.

4.5.2 Executive summary

The Mesohellenic Trough in Western Macedonia represents a large-scale CO_2 storage system whose strategic value is primarily defined by its geological capacity rather than the availability of local emission sources. Initial assessments indicate that the Pentalofos and Eptachori formations provide a combined storage capacity exceeding 1 Gt of CO_2, enabling long-term storage at regional scale and supporting multi-decadal operation [Koukouzas et al (2023), Tyrologou et al. (2025)].

From a technical perspective, the storage system is characterised by moderate porosity and relatively low permeability formations, which constrain injectivity and limit extensive plume migration. CO_2 injection is therefore governed by pressure buildup and its spatial propagation within hydraulically connected reservoir units. This defines a pressure-controlled storage regime, where effective capacity depends not only on available pore volume, but on the ability to manage pressure within thresholds associated with caprock integrity and fault stability.

The proposed development concept is based on a phased and scalable approach, targeting injection rates on the order of 3 Mt CO_2 per year over a 30-year operational period. At this scale, injection must be distributed across multiple wells and, where necessary, across different stratigraphic intervals to avoid localised pressure accumulation. This multi-layered utilisation of the reservoir system enhances operational flexibility and allows the progressive activation of storage capacity as CO_2 supply increases.

The viability of the system is strongly linked to transport integration. While local source-to-sink distances are relatively short, the long-term development of the basin depends on its connection to broader CO_2 transport networks capable of delivering external CO_2 streams. Pipeline-based transport remains the most likely option for regional integration, although the potential role of multimodal transport (including shipping) may need to be considered in future expansion scenarios.

Economic evaluation indicates that the project can achieve positive financial performance under current carbon pricing conditions, provided that sufficient CO_2 volumes are secured. Based on PilotSTRATEGY assessments, total capital expenditure for the integrated system is estimated in the range of approximately 600–800 M€, while net present value approaches 1 billion euros at a reference carbon price of around 75 €/t CO_2 [Canteli et al., 2025b, D4.9]. However, financial performance remains sensitive to key technical parameters, particularly injectivity, well requirements and infrastructure utilisation, as well as to the availability of external CO_2 supply.

The development pathway follows a staged approach, starting with detailed site characterisation and pilot-scale validation of injectivity and pressure response, and progressing toward full commercial operation. This approach enables the progressive reduction of uncertainty related to reservoir connectivity, permeability distribution and long-term pressure evolution, which are critical factors for both technical feasibility and investment risk.

From a regulatory perspective, the development of CO_2 storage in the Mesohellenic Trough is aligned with the European CCS Directive[9] and its transposition into Greek legislation, including Law

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[9] Directive 2009/31/EC on the geological storage of carbon dioxide, in 2009/31/EC. 2009, L 140/114, 5.6.2009.

4936/2022[10] and the more recent framework introduced under Law 5261/2025[11]. which define requirements for site characterisation, permitting, monitoring and long-term liability. The current level of geological understanding supports the transition from conceptual assessment toward pre-FEED level development, provided that key uncertainties are addressed through targeted field validation.

Overall, the Mesohellenic Trough represents a storage system where large capacity, structural complexity and strategic location converge. Its development is not constrained by local emission availability, but by the ability to integrate geological capacity with transport infrastructure and external CO_2 supply. Under this perspective, the basin provides a technically credible and economically viable basis for the development of a large-scale CO_2 storage hub in Greece, with the potential to support broader Southeast European decarbonisation needs.

4.5.3 Proposed development

4.5.3.1 Capture

In the case of the Mesohellenic Trough, the capture component is not considered the primary driver for CCS deployment, but rather a complementary element within a broader, storage-led system. Recent developments in the regional energy sector, including the phase-out of lignite-based power generation and the planned conversion of Ptolemaida V to natural gas operation, significantly reduce the long-term availability of large, concentrated CO_2 emission sources in Western Macedonia [Samaras et al. (2023)].

Under these conditions, a capture-driven CCS configuration based exclusively on local emission sources is unlikely to sustain the scale required for long-term operation. Instead, the proposed concept assumes that the majority of CO_2 to be stored will originate from external sources, including industrial regions with limited geological storage capacity. As a result, capture is treated as an upstream process that may occur outside the immediate project boundary, with the Mesohellenic Trough functioning primarily as a receiving and storage site.

Nevertheless, local capture opportunities may still play a transitional or supplementary role during early stages of deployment. Facilities such as Ptolemaida V, under its modified operational regime, or other industrial installations in the broader region, could provide limited CO_2 volumes that support initial injection activities and system validation. However, these sources are not expected to define the long-term capacity or economic viability of the project.

From a technical perspective, the integration of capture with transport and storage remains critical, regardless of the origin of the CO_2 stream. Captured CO_2 must be conditioned to meet transport and injection specifications, including dehydration and compression to dense phase conditions. These requirements ensure flow stability during transport and compatibility with reservoir conditions, particularly in pressure-sensitive storage systems such as the Mesohellenic Trough.

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[10] National Climate Law – Transition to climate neutrality and adaptation to climate change, urgent provisions to address the energy crisis and protect the environment., in Law No. 4936. 2022, Government Gazzette A' 105/27.05.2022.

[11] Regulations on the capture, utilisation, transport and storage of carbon dioxide – Transposition of Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide, and amending Council Directive 85/337/EEC, Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC and 2008/1/EC of the European Parliament and of the Council, and Regulation (EC) No 1013/2006 (OJ L 140). in Law No. 5261. 2025, Government Gazzete A' 231/12.31.2025.

At system level, the decoupling of capture from storage introduces additional flexibility but also shifts the focus toward securing reliable CO_2 supply chains. The performance of the storage system is directly linked to the continuity and volume of CO_2 delivered, which in turn depends on external capture infrastructure and transport integration. As a result, capture is not eliminated from the system, but repositioned as an external and variable input that must be coordinated with transport and injection strategies.

Overall, the capture component in the Mesohellenic Trough CCS concept is defined by its functional role within the value chain rather than by its geographic location. The long-term viability of the system depends less on local capture capacity and more on the ability to connect the storage complex with stable and sufficient CO_2 sources at regional scale.

4.5.3.2 Transport

The transport component constitutes a critical element of the proposed CCS system, as it enables the connection between external CO_2 sources and the storage complex of the Mesohellenic Trough. Under the storage-led development scenario, the system is not constrained by local emission availability but by the ability to ensure continuous and scalable CO_2 delivery from external sources.

At the regional scale, the relatively short distances between potential emission clusters and the storage sites favour pipeline-based transport as the primary option during early deployment phases. Distances on the order of tens of kilometres allow operation under dense-phase conditions, reducing recompression requirements and supporting stable flow regimes, which are essential for maintaining consistent injection performance [Canteli et al., 2025a, D4.3; Canteli et al., 2025b, D4.9].

As the system evolves, transport requirements extend beyond local connections. The integration of the Mesohellenic Trough into wider CO_2 transport networks introduces the need for scalable infrastructure capable of accommodating increasing flow rates and potentially variable supply conditions. This includes the design of pipelines with sufficient capacity margins and the potential integration with transnational CO_2 corridors, as considered in European CCS deployment pathways [D4.5].

From an operational perspective, CO_2 transport is expected to occur in dense or supercritical phase, typically above 80 bar, ensuring flow stability and minimising the risk of phase transitions. Upstream conditioning is required to meet transport specifications, including dehydration to avoid corrosion and hydrate formation, as well as compression to match pipeline and injection pressure conditions. Pressure losses along the transport system must be explicitly accounted for, particularly in relation to injection pressure constraints imposed by the reservoir (Table 4.20)Table 4.20).

Parameter	Typical range / assumption	Technical implication
Source-to-sink distance	~10–100 km (early phase)	Enables pipeline transport with limited recompression needs
Transport mode (initial phase)	Onshore pipeline	Continuous, high-capacity CO_2 delivery
Transport mode (expansion phase)	Pipeline + potential multimodal (shipping)	Flexibility for external and long-distance CO_2 sourcing
Operating phase	Dense / supercritical CO_2	Stable flow, reduced volume, improved transport efficiency
Operating pressure	> 80 bar	Prevents phase change and ensures flow continuity
CO_2 conditioning	Dehydration + compression	Avoids corrosion, hydrate formation and flow instabilities
Flow regime	Continuous, steady-state preferred	Supports stable injection and pressure management
Pressure losses	Function of flow rate, diameter, terrain	Must be matched with injection pressure constraints
Scalability requirement	High (phased capacity increase)	Supports transition from local to regional transport network

Table 4.2020 Key transport design parameters for the Mesohellenic CCS system

The interaction between transport and storage is particularly important in pressure-controlled systems. Variations in CO_2 supply rates directly affect injection conditions and may induce transient pressure responses within the reservoir. For this reason, transport design must ensure stable and predictable flow conditions, aligned with injection strategies and subsurface constraints.

In scenarios involving long-distance CO_2 sourcing, multimodal transport solutions, including shipping, may be introduced to complement pipeline infrastructure. Such configurations require additional handling facilities, including intermediate storage and recompression units, and introduce operational flexibility at the expense of increased system complexity.

4.5.3.3 Storage

The storage component of the proposed CCS system is centred on the deep saline formations of the Mesohellenic Trough, primarily the Pentalofos and Eptachori formations, which together provide storage capacities exceeding 1 Gt of CO_2 [Tyrologou et al. (2023), Koukouzas et al. (2023), Tyrologou et al. (2025)]. These formations are characterised by laterally extensive sandstone units, overlain by low-permeability sealing formations that provide the necessary conditions for long-term containment.

From a reservoir engineering perspective, the storage system is defined by moderate porosity and relatively low permeability, which constrain injectivity and limit rapid lateral plume migration. Under these conditions, CO_2 injection is governed by pressure buildup and its propagation within hydraulically connected reservoir compartments. This behaviour implies that effective storage capacity is not solely determined by available pore volume, but by the ability to manage pressure within operational limits imposed by caprock integrity and fault stability.

The structural framework of the basin introduces an additional level of complexity. Fault systems and lithological heterogeneity create compartmentalisation within the reservoir, which may locally restrict fluid flow but can also act to limit large-scale pressure propagation. The interaction between these features defines the spatial distribution of injectivity and requires careful well placement to ensure efficient utilisation of the storage system.

Injection strategy is therefore a critical design parameter. At the reference scale of approximately 3 Mt CO_2 per year, injection must be distributed across multiple wells to avoid localised pressure buildup. The use of multiple stratigraphic intervals further enhances system performance, allowing pressure dissipation across different reservoir levels and reducing the risk of exceeding caprock fracture thresholds or triggering fault reactivation.

Well design must accommodate the pressure-controlled nature of the system. Injection wells are expected to operate under conditions where bottom-hole pressure is maintained below critical limits, while still ensuring sufficient injectivity. This requires appropriate completion strategies, including perforation across selected intervals and, where necessary, the use of stimulation techniques to improve near-wellbore permeability.

Monitoring, Measurement and Verification (MMV) is an integral part of the storage concept. The objective is to track CO_2 migration, pressure evolution and potential leakage pathways throughout the operational lifecycle. Monitoring techniques may include pressure monitoring, seismic surveys and geochemical sampling, enabling the validation of model predictions and the early detection of deviations from expected behaviour (Table 4.21Table 4.21).

Parameter	Typical range / observation	Technical implication
Storage formations	Pentalofos, Eptachori	Primary reservoir units for CO_2 storage
Total storage capacity	> 1 Gt CO_2	Multi-decadal storage potential
Porosity	Moderate (≈10–20%)	Provides storage volume but not high injectivity
Permeability	Low to moderate	Constrains flow, increases pressure sensitivity
Flow regime	Pressure-driven	Limited plume migration, pressure-controlled system
Structural setting	Faulted and heterogeneous	Compartmentalisation affects injectivity and pressure propagation
Injection rate (reference)	~3 Mt CO_2/year	Requires multi-well configuration
Injection strategy	Multi-well, multi-layer	Reduces local pressure buildup
Pressure constraint	Below fracture & fault reactivation thresholds	Ensures caprock integrity
Well design	Controlled bottom-hole pressure	Maintains safe and efficient injection
MMV requirements	Pressure, seismic, geochemical monitoring	Verification of storage performance and containment

Table 4.2121 Key storage system parameters and operational constraints

The performance of the storage system is therefore governed by the interaction between reservoir properties, structural configuration and operational parameters. The need to control pressure evolution across the reservoir introduces constraints on injection rates and well density, while also providing a framework for optimising storage efficiency through distributed injection.

The Mesohellenic Trough is conceptualised as a pressure-managed storage system, where capacity, injectivity and containment are interdependent. The development of the storage complex depends on the ability to balance these factors through appropriate engineering design and progressive validation of subsurface behaviour.

4.5.4 Proposed planning

The development of the Mesohellenic CCS system follows a phased approach, structured around the progressive reduction of subsurface and system-level uncertainties. Given the pressure-controlled behaviour of the reservoir and the reliance on external CO_2 supply, the planning strategy is not defined solely by time, but by the sequential validation of key technical parameters that directly influence injectivity, storage capacity and operational stability.

The initial phase focuses on detailed site characterisation and model refinement. This includes the integration of existing geological, geophysical and geochemical datasets with targeted data acquisition, such as additional well data, pressure measurements and reservoir testing. The primary objective at this stage is to constrain uncertainty related to permeability distribution, reservoir connectivity and pressure propagation, which are critical for defining safe injection limits and well configuration.

Following this, a pilot-scale injection phase is required to validate reservoir behaviour under dynamic conditions. Controlled injection tests provide direct information on injectivity, pressure response and boundary effects, allowing the calibration of numerical models and the refinement of the storage concept. This phase is particularly important in systems where permeability is relatively low and pressure buildup governs performance, as is the case in the Mesohellenic Trough.

Once key uncertainties are reduced to an acceptable level, the project can transition to early commercial operation. This stage involves the deployment of a limited number of injection wells and the establishment of initial transport infrastructure, with injection rates gradually increasing toward the target range of several million tonnes of CO_2 per year. The expansion of the system is directly linked to observed reservoir performance, ensuring that injection strategies remain within pressure constraints and do not compromise caprock integrity or fault stability.

The full-scale development phase is based on the progressive expansion of both subsurface and surface infrastructures. Additional wells are introduced to distribute injection spatially, while transport capacity is increased to accommodate larger CO_2 volumes from external sources. The use of multiple stratigraphic intervals allows further optimisation of storage efficiency and pressure management, enabling the system to operate at higher injection rates without exceeding operational thresholds (Table 4.22Table 4.22).

Phase	Main activities	Key uncertainties addressed	Technical objective
Site characterisation	Data integration, additional measurements, reservoir modelling	Permeability distribution, reservoir connectivity, structural complexity	Define injectivity and pressure limits
Pilot injection	Controlled injection tests, pressure monitoring, model calibration	Injectivity, pressure propagation, boundary conditions	Validate dynamic reservoir behaviour
Early operation	Limited well deployment, initial transport infrastructure	Well performance, short-term pressure response	Establish stable injection regime
Expansion phase	Additional wells, multi-layer injection, increased transport capacity	Long-term pressure evolution, reservoir interaction	Scale injection while maintaining pressure control

Full-scale operation	Integrated system operation with external CO_2 supply	System-wide performance and operational optimisation	Maximise storage utilisation under safe conditions

Table 4.2222 Phased development plan and associated uncertainties

The timeline of these phases is inherently linked to the rate at which uncertainties are reduced rather than to fixed calendar milestones. In particular, the transition from pilot injection to early commercial operation depends on achieving sufficient confidence in injectivity and pressure behaviour, while full-scale deployment requires validated understanding of long-term reservoir response.

A critical aspect of the planning strategy is the alignment between subsurface performance and CO_2 supply. The availability of external CO_2 streams must be synchronised with the readiness of the storage system and transport infrastructure, ensuring that injection operations remain continuous and within design limits. This interdependency between capture, transport and storage introduces additional complexity, but also provides flexibility in adapting the development pathway to evolving market and regulatory conditions.

4.5.5 Economic assessment

The economic performance of the proposed CCS system in the Mesohellenic Trough is primarily driven by the interaction between storage capacity, transport infrastructure and the availability of CO_2 supply. Under the storage-led development concept, the economic viability of the system depends less on local capture costs and more on the ability to secure sufficient and stable CO_2 volumes from external sources, ensuring high utilisation of the transport and storage infrastructure.

Based on PilotSTRATEGY assessments, the total capital expenditure (CAPEX) for the integrated CCS system is estimated in the range of approximately 600–800 M€, including storage site development, transport infrastructure and associated facilities [Canteli et al., 2025b, D4.9]. This range reflects uncertainties related to well requirements, pipeline configuration and the extent of infrastructure needed to support external CO_2 sourcing.

The storage component constitutes a significant share of the total investment, primarily due to drilling costs, well completion and monitoring systems. In pressure-controlled systems such as the Mesohellenic Trough, the number of injection wells is a critical cost driver, as relatively low permeability requires distributed injection to maintain acceptable pressure levels. Consequently, injectivity directly influences both capital costs and operational efficiency.

Transport costs are closely linked to distance, flow rate and infrastructure design. For short-distance pipeline transport, capital costs remain relatively moderate, particularly when dense-phase operation reduces recompression requirements. However, under scenarios involving external CO_2 supply, additional investments may be required to expand pipeline capacity or to integrate with regional transport networks, increasing overall system cost but also enabling higher utilisation of storage capacity (Table 4.23Table 4.23).

Parameter	Indicative value / range	Economic implication
Total CAPEX (full chain)	~600–800 M€	Includes capture (external), transport and storage
Storage CAPEX share	High (wells + MMV)	Driven by well number and monitoring requirements

Injection rate (reference)	~3 Mt CO_2/year	Defines infrastructure scale and revenue potential
Project lifetime	~30 years	Multi-decade revenue stream
Carbon price (reference)	~75 €/t CO_2	Main revenue driver
NPV (indicative)	~1 billion €	Positive under full utilisation scenario
Key cost driver	Number of injection wells	Linked to injectivity and permeability
Transport cost sensitivity	Medium–high	Increases with distance and network complexity
CO_2 supply dependency	Critical	Low utilisation reduces economic performance

Table 4.2323 Key economic parameters and assumptions

The economic performance of the system is highly sensitive to a limited number of technical parameters. Injectivity is a primary factor, as it determines the number of wells required to sustain target injection rates. Lower-than-expected injectivity increases both capital and operational costs, while also limiting the achievable storage rate. Similarly, the degree of reservoir connectivity influences pressure propagation and may impose additional constraints on injection strategy, further affecting system economics.

Another critical factor is infrastructure utilisation. The storage-led concept assumes that sufficient CO_2 volumes will be available from external sources to operate the system at or near its design capacity. Under-utilisation of transport and storage infrastructure significantly reduces economic performance, as fixed costs are distributed over lower CO_2 volumes. This highlights the importance of securing long-term CO_2 supply agreements and integrating the system within broader CCS networks.

The financial model also reflects uncertainties related to transport configuration. While pipeline transport is cost-effective for short to medium distances, scenarios involving long-distance CO_2 sourcing or multimodal transport introduce additional costs associated with intermediate storage, recompression and handling facilities. These factors must be considered in future development stages, particularly if the system evolves toward a larger regional storage hub.

4.5.6 Social and environmental assessment

The environmental and social dimension of the proposed CO_2 storage system in the Mesohellenic Trough is intrinsically linked to both the geological characteristics of the site and the regulatory framework governing its development. Within the Greek context, CO_2 storage projects are classified as Category A1 activities, requiring a full Environmental Impact Assessment (EIA) prior to any exploration or operational phase. This classification reflects the strategic importance of subsurface operations and the need for comprehensive evaluation of potential impacts before project implementation [D4.7]. In line with the Environmental Impact Assessment framework applied in Greece, the Mesohellenic Trough storage project is required to evaluate a wide range of environmental receptors, including groundwater systems, surface water, soil, air quality, biodiversity and human health, as well as potential cumulative impacts associated with industrial activities in the region. The EIA process also incorporates site-specific constraints related to land use, infrastructure proximity and hydrogeological conditions, which directly influence the selection of well locations and surface facilities. In addition, mitigation measures and monitoring plans must be defined from the early design stage, while public consultation forms an integral part of the permitting procedure, ensuring that local stakeholders are informed and involved in the decision-making process [Samaras et al. (2023)].

From an environmental perspective, the performance of the storage system is directly controlled by subsurface behaviour, particularly pressure evolution and containment integrity. In pressure-sensitive systems such as the Mesohellenic Trough, environmental risk is not only related to the presence of CO_2 in the subsurface, but to how pressure propagates within the reservoir and interacts with structural features. Fault systems and lithological heterogeneity introduce both containment mechanisms and potential leakage pathways, requiring a design approach that explicitly considers caprock integrity, fault stability and well integrity under dynamic conditions.

Potential environmental risks are therefore associated with unintended CO_2 migration, including leakage through faults, legacy wells or pressure-induced pathways. These risks are addressed through a combination of conservative injection strategies and continuous monitoring. The Monitoring, Measurement and Verification (MMV) framework is a central component of this approach, covering baseline characterisation, operational monitoring and post-closure surveillance. Pressure monitoring, seismic imaging and geochemical analyses provide the necessary data to validate reservoir behaviour and detect any deviation from expected conditions at an early stage.

Within this context, the EIA process becomes directly coupled with technical design. Parameters such as injection rate, well distribution and pressure limits are not defined independently from environmental considerations but emerge as part of a system that must demonstrate controlled and predictable behaviour over time. This integration between environmental assessment and engineering design is essential in ensuring long-term containment and regulatory compliance.

The social dimension of the project is strongly shaped by the ongoing energy transition in Western Macedonia. The region has historically relied on lignite-based energy production, and the progressive phase-out of coal has led to economic restructuring and employment challenges. In this setting, the development of CO_2 storage can be interpreted not as an isolated infrastructure project, but as part of a broader transition pathway, contributing to the reconfiguration of the regional energy system and the retention of technical expertise in subsurface and energy-related activities.

At the same time, the proposed storage concept introduces a shift in the regional role within the CCS value chain. Rather than acting as a major emission source, the region is positioned as a storage destination for CO_2 streams originating from other industrial areas. This transition requires careful framing, as public acceptance may depend on how this new role is perceived. Concerns related to long-term safety, environmental protection and the origin of the stored CO_2 must be addressed through transparent communication and clear demonstration of system reliability.

An additional social factor relates to institutional and regulatory confidence. The involvement of competent authorities, such as HEREMA, and the alignment with European regulatory frameworks provide a level of assurance regarding project oversight and long-term liability management. However, the current limitations in national legislation, particularly regarding the eligibility of certain storage formations, highlight the need for regulatory evolution in parallel with technical development [D4.7].

The feasibility of the project is therefore not defined solely by technical or environmental performance, but by the combined ability to demonstrate safe operation, regulatory compliance and societal acceptance. The integration of these elements becomes a key condition for transitioning from a conceptual storage model to an implementable CCS system.

4.5.7 Risk-benefit assessment

The proposed development of CO_2 storage in the Mesohellenic Trough presents a combination of technical opportunities and constraints, which must be evaluated in an integrated manner across subsurface behaviour, infrastructure requirements and system-level dependencies. The assessment of risks and benefits is therefore not limited to individual components, but emerges from the interaction between geological conditions, engineering design and the broader CCS value chain.

A key strength of the system lies in the scale and geological suitability of the storage formations. The presence of laterally extensive sandstone units with significant storage capacity provides the basis for long-term CO_2 containment, while the existence of regional sealing formations supports the integrity of the storage complex. In addition, the structural configuration of the basin, characterised by compartmentalisation, may contribute to limiting large-scale pressure propagation and plume migration, provided that injection is properly managed. These characteristics position the Mesohellenic Trough as a technically credible storage system capable of supporting multi-decadal operation.

At the same time, the performance of the system is constrained by its pressure-controlled nature. Moderate permeability limits injectivity, requiring the use of multiple wells and distributed injection strategies to avoid localised pressure buildup. This introduces both technical and economic implications, as the number of wells becomes a key driver of project cost and operational complexity. The interaction between pressure evolution, fault stability and caprock integrity represents one of the primary technical risks, requiring continuous monitoring and conservative operational limits (Table 4.24).

A second critical factor relates to system integration and CO_2 supply. Unlike regions with strong local emission sources, the Mesohellenic concept is based on a storage-led model, where the utilisation of the system depends on the availability of external CO_2 streams. This introduces a structural dependency between transport infrastructure, market conditions and long-term supply agreements. Under conditions of insufficient CO_2 supply, the economic performance of the system is significantly reduced, as fixed infrastructure costs are not offset by corresponding storage volumes.

From a regulatory and environmental perspective, the project benefits from alignment with European CCS directives and an established EIA framework, which provide a clear pathway for permitting and oversight. However, existing limitations within national legislation, particularly regarding the eligibility of saline aquifers, introduce an additional layer of uncertainty that must be addressed through targeted regulatory updates. The need to demonstrate long-term containment, environmental protection and post-closure responsibility further reinforces the importance of robust monitoring and risk management strategies.

The social dimension introduces both enabling and constraining factors. The ongoing transition of Western Macedonia away from lignite-based energy production creates an opportunity to reposition the region within the emerging CCS value chain, supporting economic continuity and the utilisation of existing technical expertise. At the same time, the shift toward a storage-oriented role, particularly in scenarios involving CO_2 import from external regions, may influence public perception and requires careful stakeholder engagement to ensure long-term acceptance.

Strengths	**Weaknesses**
• Large-scale storage capacity (>1 Gt CO_2) supported by laterally extensive sandstone formations • Presence of regional sealing formations ensuring containment integrity • Structural compartmentalisation potentially limiting large-scale pressure propagation • Alignment with EU CCS framework and existing EIA procedures	• Pressure-controlled system with moderate permeability, limiting injectivity • Requirement for multiple injection wells, increasing CAPEX and operational complexity • Sensitivity to pressure buildup and interaction with faults and caprock integrity • Dependence on further regulatory adaptation for saline aquifer utilisation
Opportunities	**Threats**
• Positioning as regional storage solution for external CO_2 sources • Contribution to Just Transition in W. Macedonia • Integration into emerging European CO_2 transport networks • Progressive scaling toward a multi-user storage system.	• Uncertainty in long-term CO_2 supply and infrastructure utilization • Public perception challenges related to CO_2 storage and import • Delays in permitting and regulatory implementation • Technical risks linked to pressure management and fault reactivation

Table 4.24 Condensed SWOT synthesis of system-level performance and deployment conditions

The balance between these factors defines the overall feasibility of the project. The Mesohellenic Trough combines large storage potential and favourable geological characteristics with challenges related to injectivity, infrastructure development and system integration. The successful deployment of the project depends on the ability to manage pressure within the reservoir, ensure stable CO_2 supply and align technical development with regulatory and societal expectations.

Under these conditions, the Mesohellenic Trough does not represent a low-risk system by default, but rather a controllable system, where feasibility is achieved through the progressive reduction of uncertainty and the alignment of subsurface performance with infrastructure and market development.

The Prinos project represents the first industrial-scale CO_2 storage project in the Eastern Mediterranean and depicts the feasibility of repurposing existing hydrocarbon infrastructure for permanent CO_2 storage project. It is the most recent development regarding CCS in South-eastern Europe and has contributed to the clarifying the national regulatory pathway for geological storage activities. The approval of this CCS project is an important practical milestone and it demonstrates that the permitting framework, defined by the EU Directive[9], which can be successfully transposed into the Greek Law No. 5261/2025[11]. Moreover, the process has allowed the competent authorities to gain practical experience in storage complexes and environmental assessments, and long-term monitoring requirements. This evolving institutional experience significantly reduces regulatory uncertainties and at the same time creates a more favourable conditions for the development of similar CCS activities in Greece, including potential projects in formations such as the Mesohellenic Trough.

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

5. Final investment proposal for each region in local language for the main regions

With the aim of being easily understood by local administration, industry, potential investors and citizens in general, Pre-FEED and Final proposal for a concept development by each primary region, i.e. Paris Basin (France), Lusitania Basin (Portugal), and Ebro Basin (Spain), is also provided in local languages.

5.1 Bassin de Paris (France)

5.1.1 Aperçu et contexte.

Le cas français reposait sur une hypothétique injection pilote de CO_2 près d'une usine d'engrais qui émettait 99 % de CO_2 pur à un débit industriel estimé (300 kt/an correspondant à l'émission d'un réformeur de méthane) dans la formation du Dogger du Bassin parisien. Le projet pilote est conçu pour tester la faisabilité technique, la sécurité et la conformité environnementale pour un hypothétique déploiement à grande échelle du CCS. L'hypothétique injection pilote de CO_2 est limitée à 100 kilotonnes (kt) conformément à l'article R229-61 du code de l'environnement français[12].

5.1.2 Résumé exécutif

Le projet pilote CO_2 du Bassin parisien vise à démontrer la faisabilité technique et l'évaluation de l'impact environnemental de l'injection de 100 kilotonnes de CO_2 dans l'aquifère salin du Dogger (Oolithe Blanche), en tirant parti d'un cadre géologique bien caractérisé avec une couche couverture du Callovo-Oxfordien épaisse et fiable. Le projet se concentre sur les tests in silico des opérations d'injection, les technologies de surveillance et la conformité réglementaire, en tant que prélude à un déploiement à grande échelle de la capture, transport et stockage géologique du CO_2 dans la région.

Deux options d'approvisionnement en CO_2 sont évaluées : un CO_2 local provenant d'une usine d'engrais voisine nécessitant une compression sur place, et un CO_2 externe transporté par rail. Deux scénarios de positionnement des puits — sur site (puits fortement dévié avec tête de puits à l'intérieur ou près de l'usine) et hors site (puits légèrement dévié avec la tête de puits à environ 3 km de l'usine) — sont évalués en termes de coûts, de contraintes opérationnelles et d'impacts sur la surface. Les besoins de transport sont faibles, avec seulement une conduite haute pression de 3 km nécessaire dans la configuration d'injection hors site.

Les évaluations environnementales et sociales ne montrent aucune contrainte rédhibitoire, avec seulement des sensibilités modérées liées aux ressources en eau et aux infrastructures existantes. La modélisation géologique et dynamique confirme que le CO_2 injecté reste bien contenu, avec une migration latérale limitée du panache (≤ 700 m) et des effets de pression dissipés dans les mois suivants l'injection. Aucune interférence avec les puits existants ou les activités souterraines n'est attendue.

Économiquement, les principaux facteurs de coût sont le conditionnement ou l'achat du CO_2 selon les besoins du pilote, la déviation du puits et la surveillance. Le puits hors site et les scénarios

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[12] https://www.legifrance.gouv.fr/codes/article_lc/LEGIARTI000024739717

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European Union's Horizon 2020 research and innovation
programme under grant agreement No. 101022664

d'approvisionnements externes de CO_2 sont généralement moins coûteux, bien que la mise en place de puits sur site puisse offrir des avantages pour l'acceptabilité de l'utilisation des sols.

Dans l'ensemble, le projet démontre une forte faisabilité technique, un confinement robuste, un impact environnemental mineur à faible et un potentiel de coûts compétitifs à long terme, soutenant le Bassin de Paris comme un candidat prometteur pour le développement futur de capture, transport et stockage géologique du CO_2 à l'échelle industrielle.

5.1.3 Projet de développement

Les scénarios envisagés pour l'injection pilote de CO_2 sont résumés Figure 4.1

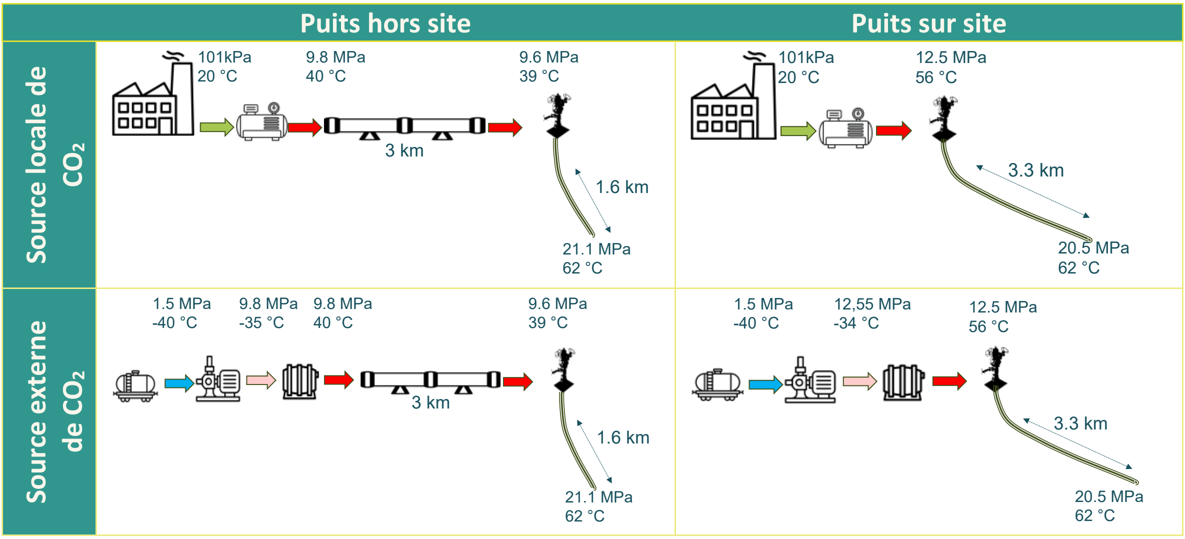

Figure 5.1 Des scénarios de développement envisagés pour un projet pilote d'injection de CO_2 dans le bassin de Paris

Le développement de l'injection pilote de CO_2 nécessiterait l'approbation des autorités françaises de régulation en vertu des codes de l'environnement et des mines via la demande de « Permis Exclusif de Recherche ». Un tel permis nécessite une évaluation des conditions environnementales, économiques et sociales de la zone d'intérêt ainsi que de son adéquation géologique pour les opérations prévues.

5.1.4 Évaluation sociale et environnementale

L'évaluation a été réalisée pour identifier et évaluer les effets potentiels du projet pilote d'injection de CO_2 sur les environnements physique, naturel et humain à travers les différentes phases du projet, y compris les travaux de construction et les opérations d'injection.

Un examen complet du contexte environnemental de la zone d'étude a été réalisé comme état initial d'un projet pilote d'injection de CO_2 afin d'évaluer les enjeux environnementaux sensibles susceptibles d'être affectés par le projet et nécessitant donc une attention particulière dans la conception et la mise en œuvre du projet. L'analyse montre que la zone d'étude se caractérise par :

- Un environnement largement anthropisé avec une sensibilité environnementale modérée,
- Aucune contrainte majeure liée au climat, à la topographie, à la qualité de l'air ou au bruit,
- Plusieurs sensibilités de niveau moyen sont principalement liées aux ressources en eau (hydrogéologie, eaux de surface, usages de l'eau), aux risques naturels, aux risques technologiques et aux infrastructures existantes.

Il est important de noter qu'aucune question environnementale très sensible ou prohibitive n'a été identifiée dans la zone d'intérêt.

Pour l'environnement physique, le projet consiste à forer pour accéder à l'aquifère salin du Dogger, bien en dessous de tous les aquifères d'eau potable. Le contexte géologique, caractérisé par des formations de roches de couverture imperméables et l'absence de failles, combiné à une conception multi-barrières des puits et à des techniques de forage contrôlées, assurent l'isolement des aquifères. En conséquence, le risque de migration du CO_2 vers les aquifères d'eau douce ou la surface est considéré comme négligeable.

En ce qui concerne l'environnement naturel, le site d'injection prévu et les infrastructures associées se trouvent en dehors des sites Natura 2000 et autres zones protégées. Bien que certains environnements naturels sensibles, notamment des rivières et une zone ZNIEFF, soient présents dans la zone d'étude plus large, ils ne seront pas directement affectés par le projet. Les impacts potentiels se limitent principalement à des perturbations temporaires et localisées lors des travaux de construction et seront réversibles.

En ce qui concerne les populations et les communautés locales, l'évaluation a identifié des impacts potentiels à court terme liés aux travaux, tels que le bruit, les émissions de poussière et l'augmentation du trafic. Ces impacts seront limités en durée et gérés par une planification appropriée, un suivi et une conformité aux exigences réglementaires et locales.

En tenant compte des problèmes environnementaux identifiés, des caractéristiques du projet et des différentes phases du projet, l'évaluation d'impact a démontré que les impacts environnementaux potentiels sont limités et bien compris. Après la mise en œuvre des mesures d'évitement, de réduction et de compensation, les impacts résiduels devraient rester faibles dans tous les secteurs environnementaux. Les évaluations environnementales, économiques et sociales détaillées sont décrites dans le rapport D4.8

5.1.4.1 Capture

Dans le cadre de son processus industriel, l'usine d'engrais émet 99 % de CO_2 pur lors du réformage du gaz naturel afin de produire l'hydrogène nécessaire à la production d'ammoniac (scénario local de la Figure 4.1). Cependant, le conditionnement du CO_2 à l'usine nécessiterait un compresseur dédié et des sécheurs pour se conformer aux conditions de pression en tête de puits pour l'injection.

En raison des incertitudes concernant les activités de l’usine, un scénario alternatif considère l'apport externe de CO_2 par train vers l'usine (scénario externe de la Figure 4.1). Comme ce CO_2 serait transporté sous forme liquide, le conditionnement du CO_2 nécessiterait un équipement dédié de déchargement ainsi qu'une pompe et un réchauffeur dédiés.

Les conceptions des équipements avec leurs caractéristiques énergétiques et des utilités sont décrites dans le rapport D4.6

5.1.4.2 Transport

Comme la zone d'intérêt pour le projet pilote potentiel se trouve autour de l'émetteur, un carboduc de CO_2 de 3 kilomètres de long serait nécessaire pour certains des scénarios envisagés, en fonction de la position possible de la tête de puits : à l'intérieur ou à proximité de l’usine (scénario sur site de la Figure 4.1) ou à la verticale de la cible du réservoir (scénario hors site de la Figure 4.1). Le carboduc de

6 pouces fonctionnerait à haute pression (environ 98 bars) et suivrait principalement les tracés des gazoducs de gaz naturel existants.

5.1.4.3 Stockage

Le domaine d'intérêt du projet pilote CO_2 a été étudié par le passé lors des travaux d'exploration des hydrocarbures. Malgré les données disponibles dans la région (voir le rapport D2.1 pour un inventaire détaillé des données disponibles), des informations supplémentaires ont été acquises pour caractériser techniquement le complexe de stockage. De nouvelles données ont été obtenues à partir d'études expérimentales et de modélisations sur les carottes du réservoir et de la couverture en ce qui concerne leurs caractéristiques pétrophysiques et l'interaction entre les fluides riches en CO_2 et la saumure in situ. La nouvelle acquisition sismique 3D a amélioré la résolution des structures géologiques et des horizons tels que décrits dans le rapport D2.3.

Après interprétation sismique et analyse stratigraphique des puits, les données ont été intégrées dans un modèle géologique, tant en termes d'éléments structuraux tels que les horizons sismiques après conversion en profondeur et les marqueurs au puits, ainsi que de les faciès et propriétés pétrophysiques telles que la porosité, la perméabilité et la teneur en argile. La formation cible est l'Oolithe Blanche (bathonienne) dans le Dogger, une rampe carbonatée à environ 1700 mètres de profondeur, à une température d'environ 60°C et une pression initiale d'environ 185 bars. La couverture ultime est constituée des marnes callovo-oxfordiennes épaisses de 120 mètres. La formation de stockage se caractérise par de fortes variations latérales et verticales de porosité et de perméabilité. De multiples réalisations ont été réalisées pour estimer un cas pessimiste, moyen et optimiste pour le volume poreux net comme proxy de la capacité de CO_2. Les résultats détaillés de la modélisation géologique sont décrits dans le rapport D3.2.

Une optimisation a été utilisée pour déterminer l'emplacement de l'injection afin de minimiser les interférences avec les activités de surface et souterraine. Par la suite, une analyse d'incertitudes a été réalisée sur les paramètres clés du modèle d'écoulement, par exemple la corrélation perméabilité-porosité, les paramètres de perméabilité relative. L'injection pilote de CO_2 de 100 kt à un débit de 300 kt/an est réalisable dans la plupart des cas. Dans certains cas extrêmes associés au modèle pessimiste, le débit d'injection ne pouvait pas être maintenu en raison de la limitation de la pression d'injection pour éviter la fracturation de la formation. La surpression correspondante peut atteindre 70 bar dans ces cas. Ces quelques cas furent ensuite abandonnés en raison de comportements dynamiques connus dans la formation. La capacité du pilote est alors vérifiée sans compromettre l'intégrité du système dans le contexte étudié. La surpression maximale est attendue autour de 3 MPa près du puits d'injection et s'étend, dans les cas extrêmes, jusqu'à 7 km pour une perturbation de 1 bar et moins de 3 km dans le meilleur des cas. Les perturbations de pression disparaissent 8 mois après la fin de l'injection. La migration du panache de CO_2 est limitée à environ 350 m du point d'injection, tandis que sa migration verticale est également limitée par des barrières d'écoulement internes à environ 90 mètres à l'intérieur de la formation bathonienne. Le panache de CO_2 n'atteint jamais la couverture pendant l'injection ni 8 mois après l'injection lors de la dissipation de pression. Les résultats détaillés de la modélisation dynamique et du positionnement des puits sont décrits dans les rapports D3.3 et D3.5.

Les résultats de la simulation pilote indiquent que le piégeage structurel prédomine initialement, représentant environ 85 à 90 % du CO_2 stocké. Cependant, un déplacement progressif vers des mécanismes de piégeage plus stables est observé au fil du temps. Après 1000 ans, la solubilité devient le mécanisme dominant, piégeant environ 70 à 75 % du CO_2, suivi d'un piégeage résiduel, qui représente 20 à 22 %. Le piégeage structurel diminue à environ 10 % à ce moment-là. Ces résultats mettent en lumière une amélioration de la sécurité du stockage au fil du temps, à mesure que la dissolution immobilise progressivement le CO_2 injecté.

Pendant la période d'injection, le CO_2 n'atteint pas la couverture et continue sa migration verticale au cours des années suivantes. Il faut environ 11 ans pour que le CO_2 dissous atteigne les marnes de Massingy (base de la roche de couverture). Après 500 ans, le CO_2 ne pénètre pas au-delà de la base de la couverture. La modélisation géochimique de la roche de couverture présente une dissolution limitée des minéraux tels que calcite et chlorite, ainsi qu'une précipitation de dolomie, indiquant des mécanismes de tampon du pH et une légère réduction de la porosité. L'impact géochimique sur la roche de couverture de l'injection pilote de CO_2 est négligeable. La description détaillée de l'évolution à long terme du CO_2 est disponible dans le rapport D3.5.

Une évaluation quantitative probabiliste des risques a été réalisée pour le projet pilote d'injection de CO_2, incluant des événements de risque pour la sécurité tels que des fuites à travers des puits existants, l'intégrité de la couverture, d'autres usages en sous-sol, des indicateurs de performance tels que l'étendue latérale du panache, la capacité de stockage et l'injectivité. L'évaluation quantitative des risques pour le pilote d'injection de CO_2 ne montre aucun risque sous-sol significatif ni interférence avec les puits ou activités sous-marines hérités, même à long terme (1000 ans), comme détaillé dans le rapport D5.2.

En considérant la position cible dans l'Oolithe Blanche et les contraintes de surface, deux scénarios (Figure 4.1) sont considérés pour l'emplacement de la tête de puits soit sur site avec un puits long et fortement dévié, soit à environ 3 km avec un puits légèrement dévié. Les conditions de la tête de puits sont calculées à partir des deux conceptions afin d'estimer la compression requise à l'usine. L'intervalle perforé de 40 mètres dans la formation de cible, Oolithe Blanche (bathonien), est défini comme recommandé dans les simulations dynamiques réalisées pour les deux scénarios à l'aide d'un liner perforé de $4^{1/2}$-pouce dans un tubage de production de 7 pouces. Les sections de puits sont définies pour protéger l'aquifère sensible de l’Albo-aptien qui est recouvert de 2 cuvelages, cimentés jusqu'à la surface. L'architecture du puits nécessite 4 ou 5 étages de cuvelage pour les cas hors site et sur site respectivement. Dans le cas hors site, la déviation du puits est d'environ 26° tandis que dans le cas sur site, la déviation est d'environ 65°. Les architectures des puits ainsi que le cuvelage, les tubages et les caractéristiques de complétion sont détaillées en le rapport D4.5. L'acquisition des données lors du forage diffère légèrement selon le cas. Elle est minimale au-dessus de la roche couverture du callovo-oxfordien et plus complète au sein de la couverture callovo-oxfordienne et des formations de stockage bathoniennes avec des diagraphies en trou ouvert et derrière cuvelage, des échantillonnages de carottes et des fluides. Après la mise en place de la complétion, un test d'injection de saumure prolongé est prévu pour évaluer l'injectivité de la formation et les barrières d'écoulement. Les détails sont présentés dans le rapport D4.6.

5.1.5 Surveillance

Le programme prévu de Mesures, Surveillance et Vérification (MMV) répond aux préoccupations clés du complexe de stockage et des installations de surface à la suite de l'évaluation qualitative des risques du projet pilote d'injection de CO_2. Différentes technologies et fréquences d'acquisition ont été définies comme illustrées Figure 4.2 et détaillées dans le rapport D4.6.

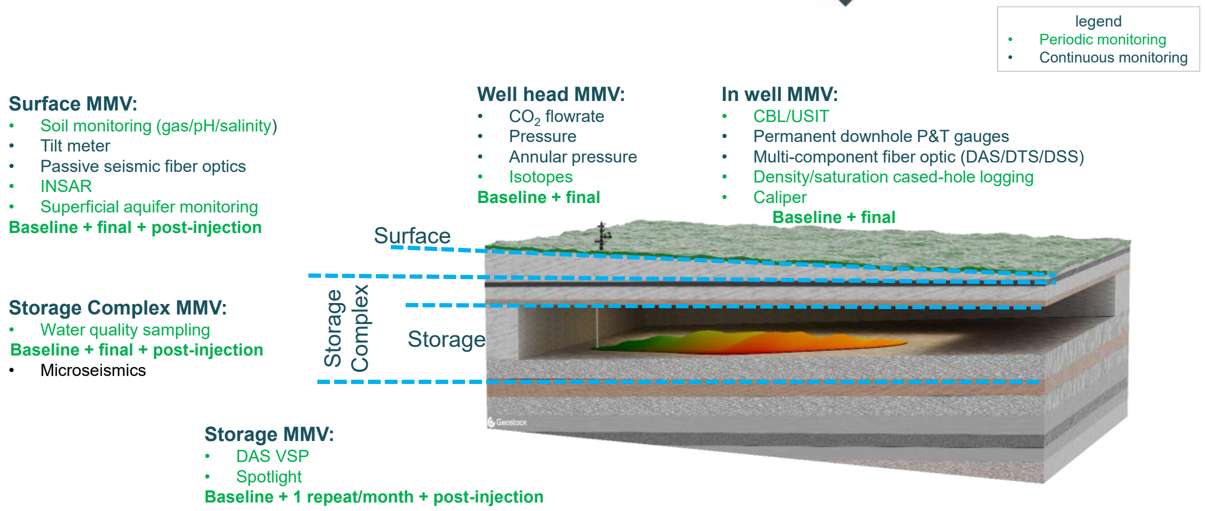

Figure 5.2 Surveillance des sous-systèmes de la géosphère pour un projet pilote d'injection de CO2 dans le Bassin parisien

5.1.6 Planification proposée

Comme détaillé dans le rapport D4.6, la planification doit prendre en compte le temps d'examen administratif de la demande de permis d'exploration et le temps nécessaire pour la livraison des éléments à long termes. Il a été envisagé que l'achat de ces équipements ne serait réalisé qu'une fois le permis accordé. De plus, la surveillance serait nécessaire pendant la migration du CO_2, comme l'imposent la directive CCS et ses documents d'orientation, qui pourrait durer jusqu'à 8 ans compte tenu des seuils de détection des mesures selon les résultats de modélisation du rapport D4.6.

En incluant le démantèlement de l'installation en surface et l'abandon du puits conformément aux exigences réglementaires, le projet pilote s'étend sur 10 ans après le dépôt du permis d'exploration tel qu'indiqué Figure 4.3.

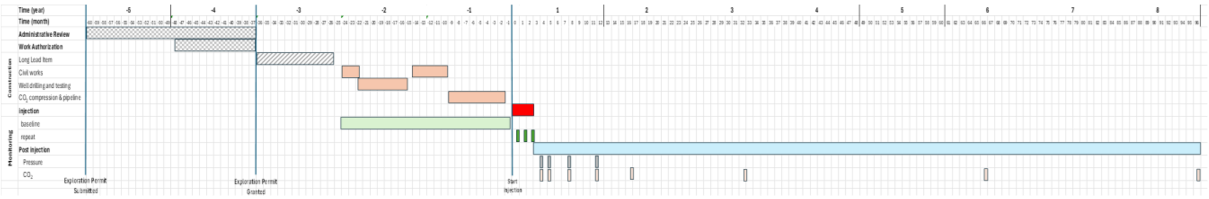

Figure 5.3: Planification prévue du cycle de vie pour un projet pilote d'injection de CO_2, depuis le dépôt administratif jusqu'à la surveillance post-fermeture.

5.1.7 Évaluation économique

Une évaluation économique probabiliste de classe IV (plage de précision −30 % à +50 %) a été réalisée et détaillée dans le rapport D4.11. Les principaux éléments économiques du scénario d'un projet pilote d'injection de CO_2 sont :

- Compresseur CAPEX (scénario avec CO_2 local de la Figure 4.1) vs. coût d'achat de CO_2 (scénario avec CO_2 externe de la Figure 4.1).
- Déviation du puits (pour le scénario sur site de la Figure 4.1 vs pour le scénario hors site de la Figure 4.1).
- Surveillance du complexe de stockage et du stockage (Figure 4.2)

Les scénarios avec un puits sur site (Table 4.1 et Figure 4.4) sont généralement plus coûteux que les scénarios avec des puits hors site en raison des coûts de forage et de complétion du puits. Les scénarios avec le CO_2 local (Table 4.1 et Figure 4.4) sont généralement plus coûteux que les scénarios avec du CO_2 externe en raison des coûts de compression nettement supérieurs aux coûts d'achat du CO_2. Cependant, il peut exister des contraintes de marché sur la disponibilité du CO_2 sur une courte période.

Compte tenu de l'évolution récente de l'activité industrielle de l'usine d'engrais et des suggestions des parties prenantes locales de minimiser l'impact du projet sur les terres, le puits sur site avec du CO_2 externe constitue une alternative intéressante au cas moins coûteux (puits hors site avec CO_2 externe), car les deux distributions se recoupent partiellement compte tenu du niveau d'incertitude montré Figure 4.4.

Scénario	**Coût total hors site** (M€2025)			**Coût total sur site** (M€2025)		
	P10	**P50**	**P90**	**P10**	**P50**	**P90**
Local CO2	64	74	85	67	76	88
CO2 externe	41	45	50	45	49	53

Tableau 5.1 Répartition du coût du projet pilote de CO_2 (CAPEX+OPEX+ABEX) (M€2025) pour les différents scénarios

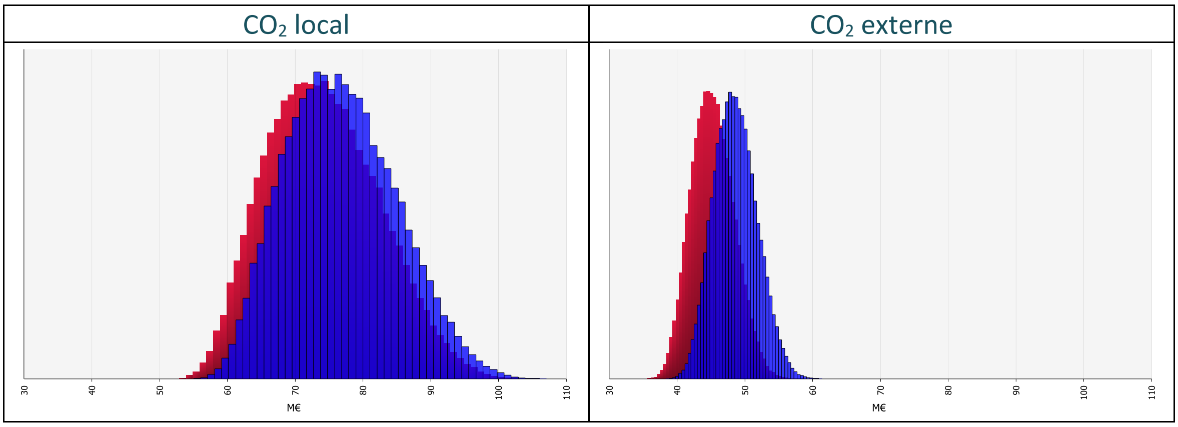

Figure 5.4 Répartition du coût du projet pilote CO_2 (CAPEX+OPEX+ABEX) (M€2025) pour le projet pilote CO2 pour le CO2 local (à gauche) et le CO2 externe (à droite) avec le puits hors site (distribution rouge) et le puits sur site (distribution bleue). Les distributions sont rapportées sur la même échelle, allant de 30 à 110 M€$_{2025}$.

5.1.8 Perspectives

Au-delà du projet pilote hypothétique de CO_2, la principale perspective économique serait le développement d'un projet de stockage commercial ne prenant en compte que la disponibilité externe du CO_2 due aux changements dans la stratégie industrielle de l'usine d'engrais. Un tel projet de stockage commercial serait élaboré sur la base des résultats pilotes et nécessiterait une approbation réglementaire pour une concession de stockage de CO_2.

Le cas commercial hypothétique étudié reposerait sur les mêmes hypothèses que le pilote d'injection de CO_2, c'est-à-dire le même débit d'injection (300 kt/an) pendant 30 ans, soit 9 Mt de CO_2, suivi d'une phase d'évolution à long terme de 1000 ans comme détaillé dans le rapport D3.4. Le scénario optimiste entraînerait une extension verticale du panache allant de 125 m à 135 m, tandis que l'extension latérale serait d'environ 2,6x2,8 km² à la fin de l'injection, évoluant ensuite jusqu'à 3,6 x 4,8 km² après 1000 ans. La surpression maximale est estimée à environ 13 bar à proximité du puits, et une perturbation de moins de 1 bar s'étendant sur environ 6 km à la fin de la période d'injection. La surpression dissiperait environ 15 ans après la fin de l'injection. L'évaluation quantitative probabiliste des risques réalisée pour le cas commercial a montré que les principaux risques sont liés à l'intégrité de trois puits anciens dans la zone, qui devront être étudiés comme détaillé dans le rapport D5.2. Une possible interférence avec les activités des concessions pétrolières actuellement actives, et qui devraient cesser ses activités en 2040[13], pourrait survenir selon la date de début de l'hypothétique phase commerciale.

Pour le projet à l'échelle commerciale, on suppose que des puits profonds de surveillance (5) seront nécessaires positionnés à la limite de l'évolution du panache attendue et un puits dans le premier aquifère au-dessus de la roche couverture, modifiant ainsi le CAPEX du projet à l'échelle commerciale. La stratégie de surveillance est supposée utiliser certaines des technologies du pilote mais à une fréquence différente pendant les périodes d'injection et de post-injection, tous les 5 ans pour le DAS-VSP pendant la période d'augmentation de pression et tous les 10 ans au-delà, avec des échantillonnages du sol et d'eau ainsi que des logs électromagnétiques, sauf pour le suivi micro-sismique en continu et l'INSAR annuellement pendant la période d'augmentation de pression. Comme montré dans le Table 4.2, ces stratégies modifient l'OPEX et par conséquent les coûts globaux du projet à l'échelle commerciale.

Coût total hors site (M€2025)			**Coût total sur site** (M€2025)		
P10	**P50**	**P90**	**P10**	**P50**	**P90**
55	59	63	57	61	66

Tableau 5.2 Répartition du coût du projet commercial de CO_2 (CAPEX+OPEX+ABEX) (M€2025) pour les scénarios de CO2 externe

Les coûts de développement commercial (Table 4.2) qui pourrait succéder à l'injection pilote de CO_2 sont estimés entre 9,1 et 10,9 $€_{2025}/t_{CO2}$. Ce coût attendu pour le développement à l'échelle industrielle peut être comparé aux estimations publiées récentes [GCCSI, 2025] : le site choisi pour le projet hypothétique d'injection de CO_2 à l'échelle commerciale correspond à l'aquifère « limite ouverte » avec une qualité de réservoir bonne à moyenne, comme montré de la Figure 4.5.

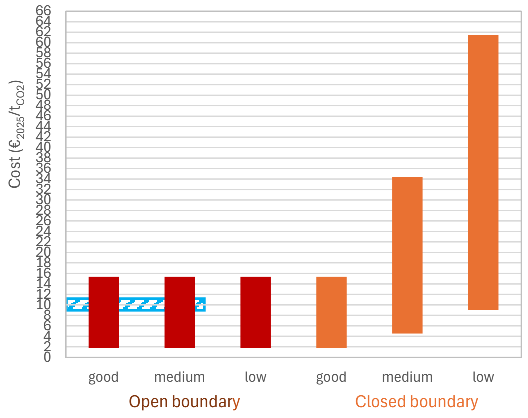

Figure 5.5 Coûts estimés du CO2 pour un projet commercial terrestre de 1 Mtpa en fonction de la qualité du réservoir (adapté du GCCSI 2025), où les zones pointillées correspondent au projet commercial de 0,3 Mtpa pour le bassin de Paris pour le CO2 externe (zone hachuré bleue)

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[13] Loi n° 2017-1839 du 30 décembre 2017 modifiant l'article L. 111-9 du code minier français.

5.1.9 Évaluation des risques et des bénéfices.

Une analyse FFOM sur le projet pilote hypothétique de CO_2 est présentée dans le Table 4.3. Les forces(F) et faiblesses (F) sont des facteurs internes au projet pilote, tandis que les opportunités (O) et les menaces (M) sont des facteurs externes.

Points forts	**Faiblesses**
• Capsule éprouvée et stockage • Plateforme industrielle dans une zone rurale • Faibles risques techniques et HSE pour la surface et le sous-sol • Plans complets de MMV	• Pas de confinement latéral • Coût du pilote • Incertitude concernant la source et le coût d'achat du CO2 pour le projet pilote
Opportunités	**Menaces**
Déploiement à l'échelle commerciale • Extension latérale limitée du CO2 • Les licences pétrolières voisines peuvent ne pas être actives au début du développement commercial • Permettre des activités industrielles neutres en carbone • Les connexions existantes (rail, routier, pipeline) peuvent devenir des centres de stockage	• Demande de licence d'exploration déjà déposée • Opposition locale au CCS • Manque de bénéfices locaux perçus induits par le projet pilote • Incertitude dans le soutien à la politique des CCS • Accès incertain aux fonds européens/nationaux pour le projet pilote

Tableau 5.3 Analyse FFOM du projet pilote CO_2 du Bassin parisien

5.2 Bacia Lusitaniana (Portugal)

5.2.1 Enquadramento

O conceito desenvolvido em Portugal no âmbito do projeto PilotSTRATEGY consiste num projeto-piloto de injeção de CO_2 na zona *offshore* do setor norte da Bacia Lusitaniana, a cerca de 22 km ao largo da cidade da Figueira da Foz. O projeto-piloto tem como objetivo avaliar: : (i) a capacidade de injeção e o comportamento do reservatório geológico; (ii) a evolução do CO_2 injetado e a capacidade de confinamento das formações geológicas; (iii) a eficácia do sistema de monitorização de segurança e de proteção ambiental; e (iv) a interação prática entre os domínios regulatórios geológico, marítimo e ambiental para a futura implementação da tecnologia de captura e armazenamento de carbono (*Carbon Capture and Storage, CCS*) à escala industrial.

O projeto-piloto deve ser entendido como um instrumento estratégico de redução de risco para alcançar as metas de neutralidade carbónica definidas pelo Estado Português, viabilizando uma alternativa de redução de emissões nas indústrias de difícil descarbonização.

5.2.2 Sumário executivo

Portugal assumiu o compromisso de alcançar a neutralidade carbónica até 2045. A concretização deste objetivo exige soluções para setores industriais de difícil descarbonização, como os setores do cimento, da cal, da gestão de resíduos e dos produtos químicos. Implica, igualmente, alcançar emissões negativas a partir de fontes de CO_2 biogénico, nomeadamente do setor da pasta e do papel. O armazenamento geológico de CO_2 é cada vez mais reconhecido como uma tecnologia essencial para a descarbonização destes setores. Contudo, Portugal não dispõe ainda de infraestruturas operacionais de armazenamento de CO_2 que permitam planear a implementação da tecnologia a uma escala que sirva o interesse nacional. Assim, um projeto-piloto de armazenamento de CO_2 é um passo necessário para viabilizar a futura implementação de CCS.

O PilotSTRATEGY propõe a implementação de um projeto-piloto de armazenamento de CO_2 no *offshore* em Portugal, visando o prospeto Q4-TV1 na Bacia Lusitaniana, ao largo da Figueira da Foz (Figura 5.6). O projeto-piloto irá injetar até 100 quilotoneladas (kt) de CO_2 no âmbito de um projeto de investigação e demonstração que integra pressupostos de captura, logística modular, um poço de injeção vertical e um plano abrangente de Monitorização, Medição e Verificação (MMV). No decurso do projeto-piloto, serão realizados testes do sistema de injeção de CO_2 a mais de 1100 m de profundidade, de tecnologias de monitorização e a verificação da conformidade regulatória, como precursor de uma possível implementação de CCS à escala industrial.

O CO_2 para o projeto-piloto será proveniente da fábrica de cimento de Souselas, mas considera um plano de contingência com CO_2 proveniente de fontes da indústria de pasta e papel nas proximidades da Figueira da Foz. O piloto prevê o transporte multimodal por via-férrea e marítima de CO_2 em contentores criogénicos e a injeção direta a partir do navio. **Esta abordagem evita a construção de infraestruturas permanentes, privilegiando a flexibilidade, a reutilização de equipamentos e a minimização do risco e do investimento irreversível.**

O reservatório geológico é composto por sedimentos siliciclásticos do Cretácico Inferior do Grupo de Torres Vedras/Formação de Figueira da Foz, a mais de 850 m abaixo do nível médio da água do mar, subjacente a uma camada de rocha selante de muito baixa permeabilidade que assegura a contenção do CO_2. A modelação e a análise de evolução da pluma de CO_2 para períodos de tempo da ordem dos 1000 anos, confirmam a contenção do CO_2 no reservatório e revelam uma transição progressiva para mecanismos de retenção que aumentam a segurança ao longo do tempo. As avaliações de segurança e desempenho concluíram que o projeto-piloto pode ser operado com um perfil de risco muito baixo, sem riscos significativos, desde que o plano MMV proposto e as medidas de mitigação sejam implementados.

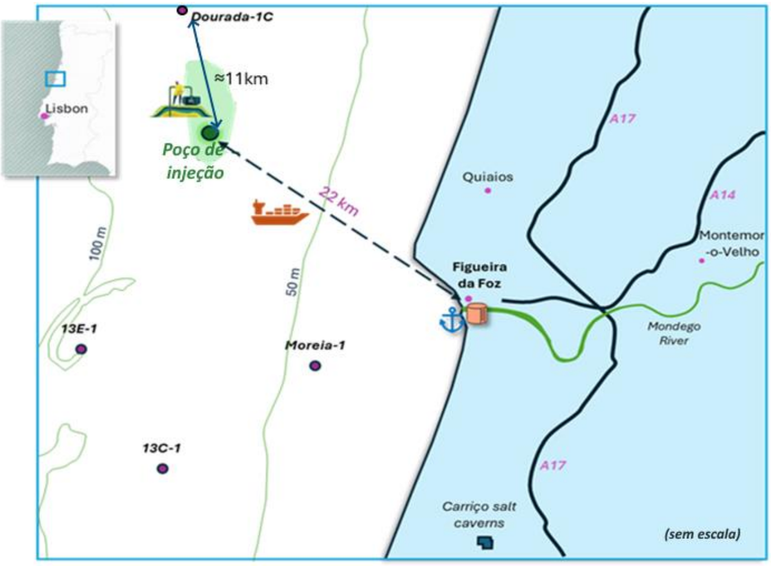

Figura 5.6: Localização do projeto-piloto de armazenamento de CO_2.

O projeto-piloto está orientado para a aquisição de conhecimento sobre o comportamento do complexo de armazenamento, mas tem em conta os impactes sociais e ambientais, devendo ser desenvolvido em estreita cooperação com as partes interessadas, ao nível regional e local. As avaliações ambientais e sociais preliminares não revelam restrições proibitivas, sendo os principais pontos sensíveis a definição das condições de referência (*baseline*) do ambiente marinho, a compatibilidade com as outras utilizações do espaço marítimo, as operações portuárias e os impactes temporários dos trabalhos inerentes à construção do piloto no *offshore*. A localização *offshore* limita os impactes diretos para a população, e a escala do projeto-piloto e opção por infraestruturas temporárias resultam numa pegada ambiental reduzida.

Em termos económicos, os principais fatores de custo (excluindo a captura de CO_2, não contabilizada no projeto PilotSTRATEGY) são a perfuração e a completação do poço de injeção, o sistema de injeção direta “navio-poço”, a logística ferroviária e marítima, bem como a aquisição de dados de sísmica de reflexão e o plano MMV necessários para validar o complexo de armazenamento e apoiar o futuro aumento de escala. **A avaliação de custos (classe IV) aponta para um investimento total de aproximadamente 98 milhões de euros, para a implementação do projeto-piloto entre 2027 e 2033.**

5.2.3 Conceito do projeto-piloto

O conceito é fortemente influenciado por três condições centrais. Em primeiro lugar, Portugal comprometeu-se a alcançar a neutralidade carbónica até 2045, o que aumenta a relevância da tecnologia de CCS para os setores de difícil descarbonização. Em segundo lugar, o país não dispõe, atualmente, de capacidade operacional de armazenamento de CO_2. Em terceiro lugar, existem desafios regulatórios significativos para a realização de armazenamento em *offshore* no país. Assim, o projeto-piloto foi concebido como um projeto de investigação e demonstração[14] que injetará até 100 kt de CO_2, mantendo um nível robusto de segurança e monitorização, procurando responder aquelas condições centrais e reforçar o posicionamento nacional na gestão de carbono. (Tabela 5.5)

Tabela 5.5: Dimensão estratégica do projeto-piloto

Dimensão Estratégica	Contribuição do Projeto Piloto
Política climática	Apoia a meta de neutralidade carbónica em 2045, preparando uma opção nacional de armazenamento de CO_2 e permitindo obter emissões negativas a partir de CO_2 de origem biogénica.
Necessidade industrial	Responde às necessidades de setores de difícil descarbonização como cimento, cal, refinação de produtos petrolíferos ou gestão de resíduos.
Preparação de infraestruturas	Valida o primeiro passo rumo a um sistema português de transporte e armazenamento de CO_2, começando com um piloto *offshore* à escala de I&D.
Posicionamento europeu	Posiciona Portugal nas estratégias europeias de gestão de carbono.

5.2.3.1 Captura

O dimensionamento do projeto-piloto tem como pressuposto a obtenção de CO_2 a partir da fábrica de cimento de Souselas. Uma possível fonte alternativa de CO_2, caso o projeto piloto de captura não seja implementado em Souselas em tempo útil, é fornecida pelas fábricas de pasta e papel situadas perto da Figueira da Foz. Uma vez que o piloto está concebido como um projeto de investigação e demonstração, a ênfase não recai na rentabilidade económica da captura, mas sim na garantia da disponibilidade de um fluxo de CO_2 tecnicamente adequado. Assim, o projeto-piloto não dimensiona

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[14] O artigo 2.º do Decreto-Lei n.º 60/2012, que transpõe a Diretiva 2009/31/CE da UE relativa ao armazenamento geológico de CO_2 (Diretiva CCS), isenta os projetos que injetem menos de 100 kt para fins de investigação dos procedimentos de licenciamento para o armazenamento de CO_2.

a componente de captura, mas considera as fases de condicionamento subsequentes (Figura 5.7), incluindo a compressão, a desidratação e a liquefação de CO_2 até aproximadamente 15 bar e -29 °C.

5.2.3.2 Transporte

O CO_2 é transportado em contentores criogénicos por via-férrea das instalações de captura até ao porto da Figueira da Foz, numa distância de cerca de 55 km, transferindo-se então os contentores para um navio que efetuará o transporte ao longo de 22 km até ao local de armazenamento. A injeção é efetuada por ligação direta entre o navio e a o poço de injeção, evitando a instalação permanente de gasodutos, de infraestruturas de armazenamento intermédias e de plataformas *offshore*. Serão transportadas e injetadas até cerca de 650 toneladas de CO_2/dia, o que corresponde a 152 viagens de ida e volta para transportar um máximo de 99 kt de CO_2. A fase de injeção deverá estender-se durante até 15 meses, decorrendo, posteriormente, a fase de monitorização pós-injeção. A cadeia logística prevista inclui (Figura 5.7):

- transferência de CO_2 condicionado/liquefeito para contentores criogénicos compatíveis com o transporte ferroviário;
- transporte ferroviário até ao porto da Figueira da Foz;
- manuseamento no porto para transferência dos contentores para o navio;
- transporte marítimo até ao local piloto em *offshore*;
- ligação direta do navio à cabeça de poço para injeção direta.

Esta cadeia logística modular é adequada para a fase piloto, embora seja operacionalmente mais complexa do que uma solução de gasoduto fixo, pois minimiza as necessidades de infraestruturas permanentes e maximiza a flexibilidade. A configuração proporcionará, adicionalmente, experiência operacional relevante para cadeias de transporte em maior escala que incluam o transporte marítimo a partir de fontes de CO_2 situadas mais na zona sul do país.

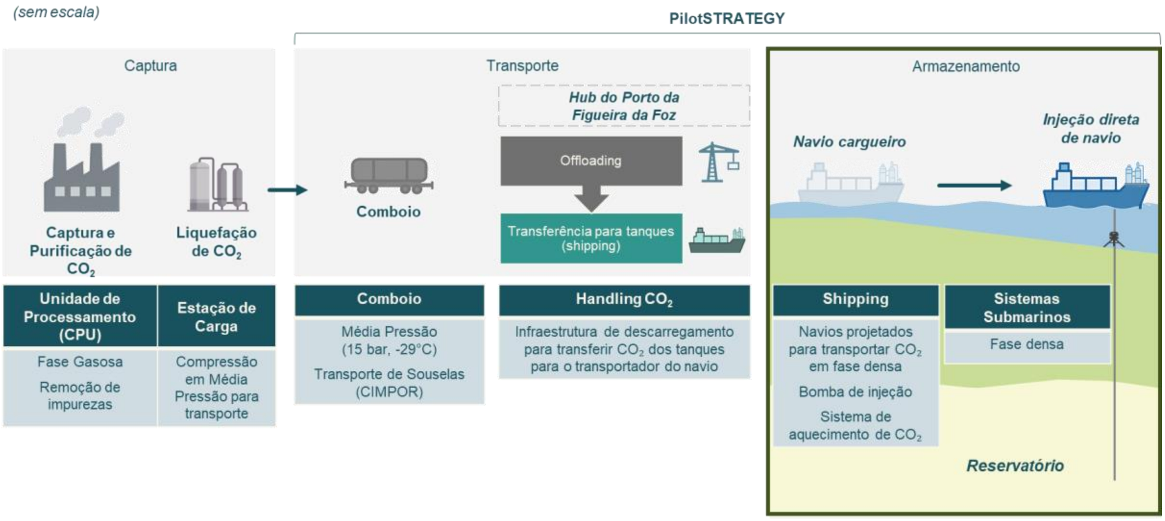

Figura 5.7: Componentes do projeto-piloto. Os parâmetros de condicionamento de CO_2 são indicativos e podem variar de acordo com as condições operacionais.

5.2.3.3 Armazenamento

O armazenamento será efetuado por injeção de CO_2 no prospeto Q4-TV1, localizado na Bacia Lusitaniana *offshore,* em águas pouco profundas (cerca de 85 m). O reservatório alvo corresponde ao Grupo de Torres Vedras/Formação de Figueira da Foz, composto predominantemente por arenitos e conglomerados, a profundidades de aproximadamente 850 a 1200 m abaixo do nível médio do mar, proporcionando condições adequadas e seguras para a injeção de CO_2.

A contenção é assegurada por múltiplas barreiras de rochas selantes, identificadas na avaliação de risco do projeto (D5.4). O selo primário é constituído pela Formação de Cacém, composta por margas de baixa permeabilidade, carbonatos e litologias ricas em argila, que se sobrepõem diretamente ao reservatório. O sistema selante é complementado por um selo secundário composto pelo Grupo de Aveiro, a menor profundidade, proporcionando uma barreira espessa e reforçando a robustez da contenção a longo prazo. Esta configuração de complexo de armazenamento com múltiplas camadas selantes é um fator chave para a segurança do armazenamento de CO_2.

A análise do reservatório indica condições favoráveis de injectividade, com uma taxa de injeção estimada entre aproximadamente 0.5 e 1.1 milhões de toneladas (Mt) de CO_2/ano para o poço de injeção. A capacidade total de armazenamento do prospeto Q4-TV1 e da área circundante está estimada em 93 $MtCO_2$, confirmando a adequabilidade do local para uma futura escala industrial.

O projeto-piloto contempla um único poço, com condições de injeção otimizadas através da modelação dinâmica do reservatório e com intervalos de injeção previstos a cerca de 1155 m e 1205 m de profundidade. A estratégia de injeção garante que a pressão do reservatório é sempre inferior a 165 bar, de modo a evitar uma sobrepressão excessiva e reduzindo os riscos de fracturação da rocha selante primária ou de reativação de falhas. A localização do poço garante que a pluma de CO_2 permanece a uma distância segura do furo antigo de prospeção de petrolífera Dourada-1C, com os resultados da modelação a não indicarem qualquer possibilidade de fuga de CO_2 através desse furo abandonado. Além disso, os dados regionais indicam baixo risco sísmico na área, enquanto uma gestão adequada da pressão garante que o risco de sismicidade induzida permanece muito baixo.

Durante a injeção, o comportamento do CO_2 no reservatório é dominado pelo mecanismo de retenção estrutural e estratigráfica (80 %), dissolvendo-se nessa fase cerca de 15–20 % na água existente no reservatório. Após o término da fase de injeção, a pressão diminui rapidamente (para cerca de 130 bar), limitando a migração da pluma. A retenção residual torna-se dominante (60–70%) ao longo de décadas a séculos, enquanto a retenção por dissolução aumenta para 25–30% ao longo de 1000 anos. A retenção estrutural e estratigráfica diminui para níveis muito reduzidos (<5%) e a retenção mineral permanece insignificante (<1%). Em geral, a rápida dissipação da pressão e a evolução dos mecanismos de retenção reduzem fortemente a mobilidade do CO_2, garantindo o confinamento e aumentando a segurança do armazenamento.

Um dos principais do projeto-piloto é gerar dados para a validação do comportamento do reservatório e do desempenho do sistema de contenção. O projeto-piloto irá, por conseguinte, implementar um sistema abrangente de MMV, concebido para dar resposta às principais incertezas identificadas nas simulações do reservatório (D4.6), incluindo a evolução da pressão, a migração da pluma de CO_2, a integridade do sistema de contenção e a potencial interação com o ambiente marinho. O plano de MMV integra:

- dados 3D de sísmica de reflexão para definição da situação inicial de referência, *Distributed Acoustic System* (DAS), e Spotlight™ para monitorizar o desenvolvimento da pluma de CO_2;
- monitorização da pressão e temperatura no fundo do poço para verificar a resposta do reservatório e a pressão induzida;

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- monitorização da sismicidade natural e induzida, usando um sistema de decisão baseado em *Traffic Light System*;
- monitorização da integridade do poço de injeção;
- caracterização da situação ambiental marinha e seu acompanhamento para detetar potenciais impactes.

Esta abordagem de MMV permite uma comparação direta entre as previsões dos modelos e o comportamento observado, proporcionando uma base sólida para a validação das condições operacionais do reservatório e do sistema de contenção.

5.2.4 Proposta de Planeamento

O projeto-piloto estende-se de 2027 a 2033, num processo faseado destinado a reduzir os riscos de investimento, e tem em conta a necessidade de autorizações marítimas, procedimentos ambientais, a contratação de navio para a aquisição sísmica, a logística ferrovia-porto e a disponibilidade de capacidade de perfuração *offshore* (Tabela 5.6).

Tabela 5.6: Calendário do projeto-piloto.

Período	Fase
2027–2028	Licenciamento, EHSIA (Avaliação de Impactos Ambientais, de Saúde e Sociais), situação ambiental, concurso para sísmica e FEED (*Front End Engineering design*).
2028–2029	Aquisição sísmica, processamento e reavaliação geológica, engenharia e detalhe do MMV.
2029–2030	Aquisição, licenciamento e preparação para trabalhos *offshore*.
2030	Perfuração e completação do poço de injeção.
2031–2032	Operações de injeção de CO_2.
2032–2033	Monitorização e avaliação pós-injeção.

Este calendário é indicativo e sujeito a incertezas, particularmente no que diz respeito a possíveis de autorizações, aquisição de sísmica 3D e janelas operacionais *offshore*. Ainda assim, a **abordagem faseada permite a validação gradual dos aspetos técnicos e regulatórios antes de se avançar para o desenvolvimento à escala industrial.**

5.2.5 Avaliação Económica

Foi realizada uma avaliação probabilística de custos seguindo o quadro económico comum (Classe IV) do PilotSTRATEGY. A natureza *offshore* do projeto e a ausência de infraestruturas existentes são os principais fatores de custo à escala piloto.

O investimento total mais provável (CAPEX + OPEX + ABEX) é de aproximadamente 98 M€ (Tabela 5.7), com um nível de incerteza entre 90–120 M€. Os principais fatores de custo são a aquisição de sísmica 3D, a perfuração *offshore* e as infraestruturas de injeção direta a partir de navio. Estes custos refletem tanto o contexto *offshore* como o carácter pioneiro do projeto. O piloto deve, por isso, ser interpretado como um investimento orientado para redução de risco, e não como um serviço de transporte e armazenamento otimizado em termos de custos.

Tabela 5.7: Síntese da estimativa de custos do projeto-piloto.

Componente	CAPEX (M€)	OPEX (M€)	SUBTOTAL (M€)
Condicionamento de CO_2	3.7	0.9	4.6
Operações ferroviárias e portuárias	-	4.3	4.3
Transporte marítimo e operações	3.0	11.4	14.4

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Submarino (ligação do navio ao poço)	25.0	1.3	26.3
Perfuração e completação do poço	30.0	1.5	31.5
Aquisição Sísmica 3D	13.8	-	13.8
ABEX	-	-	3.1
Total			**98**

5.2.6 Avaliação social e ambiental

O projeto-piloto servirá como um caso de teste para definir protocolos de monitorização adequados para o armazenamento de CO_2 nas condições da zona *offshore* portuguesa. A avaliação social e ambiental não indica qualquer restrição proibitiva na fase de conceito, mas confirma que a definição da situação ambiental marinha e a monitorização são fundamentais para a aceitabilidade do projeto. O carácter *offshore* do piloto reorienta os principais focos de sensibilidade, afastando-os dos conflitos diretos associados ao uso do solo e direcionando-os para a necessidade de proteção ambiental e compatibilidade com os diversos usos do espaço marítimo e das infraestruturas portuárias. As principais questões identificadas incluem a perturbação temporária durante a aquisição de dados sísmicos e a perfuração, interações com habitats bentónicos e a química da coluna de água, devendo o planeamento demonstrar que as perturbações relacionadas com o projeto (sísmica 3D, perfuração, MMV) permanecem dentro de limites aceitáveis e reversíveis.

A lógica de mitigação proposta baseia-se em estudos ambientais de referência realizados numa fase inicial, num plano de MMV integrado, num planeamento cuidadoso das operações *offshore,* e na coordenação com as outras atividades existentes na zona (nomeadamente, a pesca) e com as autoridades competentes. Em geral, os impactes ambientais e sociais são controláveis e não constituem um obstáculo, desde que a monitorização, as medidas de mitigação e o envolvimento das partes interessadas sejam devidamente implementados e transparentes.

5.2.7 Avaliação de Riscos e Benefícios

Em termos de riscos e benefícios, o projeto-piloto da Bacia Lusitaniana combina um forte potencial estratégico com os desafios esperados de uma demonstração *offshore* pioneira, tal como ilustrado na análise SWOT (Tabela 5.8).

Tabela 5.8- Análise SWOT do projeto piloto na Bacia Lusitaniana.

Pontos fortes	**Pontos fracos**
• parte da solução necessária para apoiar os setores nacionais de difícil descarbonização; • prospeto de armazenamento *offshore* identificado na Bacia Lusitaniana; • forte relevância estratégica para a preparação a de uma infraestrutura CCS nacional; • conceito como atividade de investigação adaptada às atuais restrições regulatórias; • conceito logístico modular para maior flexibilidade e reduzir infraestruturas permanentes na fase piloto.	• custos unitários elevados devido ao desenvolvimento de um projeto piloto *offshore* pioneiro; • incertezas relativamente ao desempenho geológico e à execução *offshore*; • complexidade da cadeia logística intermodal; • questões regulatórias.
Oportunidade	**Ameaças**
• criação da primeira experiência operacional com armazenamento geológico de CO_2 em Portugal; • geração do conhecimento técnico e regulatório necessário para futuros projetos comerciais;	• atrasos associados ao licenciamento *offshore* e à coordenação entre autoridades; • aumento dos custos na perfuração *offshore* ou na logística;

• apoio a setores de difícil descarbonização no âmbito de um objetivo de neutralidade carbónica; • posicionamento de Portugal nas políticas europeias de gestão de carbono.	• requisitos de monitorização ambiental superiores ao esperado; • continuidade insuficiente da fase piloto para o seguimento comercial.

5.2.8 Potencial de expansão

O projeto-piloto está explicitamente enquadrado como um projeto de I&D, mas a ser bem-sucedido poderá permitir a partir de 2034 a implementação de um projeto à escala industrial, inicialmente com uma capacidade de injeção de 0,5–1,1 $MtCO_2$/ano no poço de injeção do projeto-piloto, mas expandindo progressivamente para um cenário com CO_2 proveniente de 14 fontes industriais dos setores do cimento, cal, refinação de petróleo, gestão de resíduos e pasta e papel. Uma avaliação detalhada indica que esses setores poderão disponibilizar até um máximo de 9,3 $MtCO_2$/ano para captura e armazenamento no horizonte 2035–2065, dos quais cerca de 60% de origem biogénica permitindo a geração de emissões negativas essenciais para alcançar a meta de neutralidade carbónica em 2045.

A transição para a fase industrial implica o abandono de uma logística modular (ferroviário e marítimo) para infraestruturas dedicadas de transporte por gasoduto no *onshore* e *offshore*, com uma rede de cerca de 700 km ao longo da faixa costeira, refletindo a distribuição espacial das principais fontes de emissão. O transporte por navio poderá manter relevância para fontes de CO_2 mais distantes, em Setúbal e/ou Sines. Nesta fase, o sistema evolui de uma configuração piloto com um único poço para um sistema de armazenamento com múltiplos poços de injeção e a utilização de diversos locais de armazenamento no sector Norte da Bacia Lusitaniana.

Em termos gerais, o percurso de expansão corresponde ao desenvolvimento de um sistema de transporte e armazenamento de CO_2 baseado em *clusters*, integrando progressivamente múltiplas fontes industriais e expandindo a capacidade de armazenamento na Bacia Lusitaniana.

5.2.9 Necessidades e desafios regulatórios

O armazenamento de CO_2 na zona *offshore* de Portugal envolve múltiplos organismos da Administração Pública, nomeadamente a Direção-Geral de Energia e Geologia (DGEG), a Direção-Geral de Recursos Naturais, Segurança e Serviços Marítimos (DGRM), e a Agência Portuguesa do Ambiente (APA). O projeto-piloto constitui uma oportunidade para estabelecer mecanismos de licenciamento coordenados e simplificados entre estas instituições, agilizando uma eventual implementação da tecnologia à escala industrial.

Embora o projeto-piloto possa ser implementado no âmbito do quadro regulatório existente como investigação e demonstração, a transição para o armazenamento de CO_2 à escala industrial exige a resolução de desafios regulatórios. Um primeiro requisito fundamental diz respeito à integração do armazenamento de CO_2 no PSOEM[15]. O atual PSOEM não atribui explicitamente áreas para o armazenamento geológico de CO_2. Será, portanto, necessário o desenvolvimento de um plano de afetação que defina as áreas *offshore* adequadas para permitir a implementação da CCS à escala industrial.

Um segundo desafio diz respeito à governação dos recursos geológicos *offshore*. Os reservatórios de armazenamento de CO_2 enquadram-se na categoria mais ampla de depósitos minerais, mas as responsabilidades pelos depósitos minerais no espaço marítimo não estão, atualmente, claramente

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[15] Plano de Situação Ordenamento do Espaço Marítimo, estabelecido pela Resolução do Conselho de Ministros n.º 203-A/2019.

definidas[16]. A clarificação das competências institucionais será essencial para um quadro de licenciamento coerente. Por último, é necessário confirmar explicitamente que o armazenamento de CO_2 não está sujeito à moratória sobre mineração em mar profundo[17], a fim de evitar ambiguidades jurídicas que poderiam inviabilizar a atividade.

Por último, Portugal não dispõe de um quadro regulatório específico para o transporte de CO_2 por gasoduto. Embora a futura legislação da União Europeia possa proporcionar uma base comum, é essencial que os procedimentos de licenciamento, as normas técnicas e as responsabilidades relativas às infraestruturas de transporte sejam clarificadas a nível nacional num prazo compatível com o início das operações comerciais.

Atingir os objetivos de neutralidade carbónica nacionais e a compatibilizá-los com a viabilidade de determinados setores industriais não será possível sem o recurso à tecnologia de captura e armazenamento geológico de CO_2. O trabalho desenvolvido no projeto H2020 PilotSTRATEGY permite avançar para a concretização de um projeto-piloto que comprove a viabilidade da tecnologia. Porém, a meta de neutralidade carbónica e as necessidades da indústria exigem decisões institucionais céleres e coordenadas, não só para financiamento e implementação do projeto-piloto, mas também para a comunicação transparente sobre a relevância desta tecnologia para o interesse nacional.

5.3 Cuenca del Ebro (España)

5.3.1 Visión general y contexto

La cuenca del Ebro estudia una formación rocosa en tierra (la estructura de Lopín, España) para evaluar como posible almacén geológico de CO_2. La zona se encuentra al noreste de España, en una zona muy poco poblada (3 pequeños pueblos de 1500 habitantes a 10 km de distancia), en un entorno rural sin grandes desarrollos agrícolas cercanos, y con presencia de potenciales emisores en la zona (industria papelera y valoración energética), a una distancia máxima de unos 60 km. Los datos del Instituto Geográfico Nacional identifican esta zona como una actividad sísmica natural muy baja.

El subsuelo de Lopín ha sido investigado en proyectos previos (ALGECO2, STRATEGY CCUS), y basada en esta información, se entiende que dicha estructura presenta un entorno geológico favorable: un acuífero salino profundo con buena extensión regional y sellos competentes (arcillas triásicas y evaporitas) que aíslan el yacimiento de formaciones poco profundas y de la superficie. El rango de capacidad de almacenamiento se ha estimado entre 2 millones de toneladas (Mt) y 35 Mt teniendo en cuenta la información actual y las incertidumbres existentes.

El estudio de la cuenca del Ebro se centra en la exploración y desarrollo de un posible almacenamiento, incluyendo una fase de exploración, una fase precomercial (piloto) y un análisis de fase comercial, con el objetivo de (1) evaluar el impacto de una incertidumbre geológica significativa, (2) identificar una estrategia de desarrollo que se adapte adecuadamente a la zona para promover esta estructura de un proyecto piloto a uno comercial, y (3) evaluar la viabilidad tecno-económica de este desarrollo comercial

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[16] O Decreto-Lei n.º 30/2021, no seu artigo 3.º, n.º 2, refere que os depósitos minerais localizados no espaço marítimo nacional estão sujeitos a legislação especial. No entanto, não revoga o Decreto-Lei n.º 60/2012, que atribui à Direção-Geral de Energia e Geologia (DGEG) a competência para agir no âmbito do quadro jurídico estabelecido em matéria de armazenamento de CO_2.

[17] A Lei n.º 36/2025 estabelece uma moratória sobre a exploração mineira em águas profundas até 1 de Janeiro de 2050, incluindo as atividades de prospeção e exploração.

basándose en un calendario, actividades y costes realistas como base para futuros responsables de la toma de decisiones.

El diseño y los costes de captura y transporte de CO_2 no se incluyen en este análisis y, solo por motivos de validación de escenarios, se ha identificado, al menos, una opción válida en ambos casos. Se asume que el CO_2 entregado cumple con las especificaciones adecuadas.

5.3.2 Resumen ejecutivo

El proyecto de almacenamiento de CO_2 en la cuenca del Ebro propone el análisis completo del ciclo vivo de una estructura terrestre, incluyendo la fase de exploración, una fase piloto de inyección o precomercial de 3 años, y una fase de desarrollo comercial. El posible almacén de Lopín es un acuífero salino profundo de edad triásica situado en el noreste de España, en la zona de Belchite (provincia de Zaragoza, España), una arenisca silícea a ~1.700 m de profundidad bajo un grueso sello rico en arcilla. Aunque el sello primario no está bien documentado, una formación impermeable secundaria y regional está bien definida y asegura una barrera para posibles fugas. Como limitaciones efectivas para el desarrollo de este almacén, la estructura de Lopín presenta sobrepresión natural y baja permeabilidad, lo que proporciona un margen operativo estrecho antes de alcanzar la presión de fractura de la capa impermeable primaria.

El desarrollo presentado se inicia con la solicitud de un permiso de exploración: los datos geológicos existentes son de 1970 a 1980 y, aunque la geología regional es bien conocida, se necesitan nuevos datos para reducir las incertidumbres geológicas actuales, razón para iniciar la evaluación mediante una adquisición de datos en una fase de exploración. Suponiendo un éxito geológico, un desarrollo piloto se define por la inyección de 100 kt de CO_2 durante aproximadamente 3 años a través de un solo pozo, lo que permitiría evaluar, en condiciones reales, la respuesta del yacimiento, la eficacia del sellado geológico y las técnicas de monitorización de CO_2. Los estudios iniciales indican que el depósito puede acomodar esta inyección piloto sin riesgos significativos. Asumiendo la validación de la estructura de almacenamiento, se llevaría a cabo un desarrollo comercial, operando hasta que se alcanza la capacidad estimada máxima, momento en el que se iniciaría el abandono.

Las fases de exploración, piloto y comercial se evalúan tecno económicamente mediante enfoques deterministas y probabilísticos para cubrir toda la gama de incertidumbres y el impacto en los parámetros de toma de decisiones económicas para la propuesta previa a la inversión.

5.3.3 Desarrollo propuesto

Siguiendo la metodología aplicada en la cuenca de París y la cuenca de Lusitania, el equipo español ha definido un escenario precomercial (fase de exploración y piloto con una inyección total de aproximadamente 100.000 toneladas de CO_2 durante 3 años a través de un solo pozo) y, condicionado al éxito de esto, un escenario comercial a mayor escala con uno o dos pozos inyectores dependiendo de la capacidad total estimada, entre 2 y 35 millones de toneladas. En ambos casos, piloto/precomercial y comercial, se asume la disponibilidad de CO_2 de una fuente industrial cercana; por lo tanto, los costes de captura y transporte no se incluyen en este análisis, y se asume que el CO_2 entregado cumple con las especificaciones adecuadas. Este enfoque aislado permite evaluar de forma realista la viabilidad técnica y económica del almacenamiento en Lopín, comparando alternativas de desarrollo. El objetivo general es determinar si esta estructura de la Cuenca del Ebro puede avanzar hacia una solución de captura, transporte y almacenamiento de carbono (CCS) viable técnica y comercialmente dentro del marco regulatorio actual español y europeo, basándose en una evaluación determinista y probabilística para la toma de decisiones.

- **Fase de exploración:**

A partir de un permiso exploratorio solicitado en 2027, se incluyen en la fase de exploración un estudio G&G (revisión de la geología y geofísica), incluyendo una campaña sísmica 2D/3D e interpretación, así como el diseño, perforación y pruebas exploratorias de un pozo. Se estima que la duración total de la fase de exploración sería entre 4 y 6 años.

Figura 5.8: Piloto y desarrollo comercial propuesto

- **Fase piloto (precomercial o demostrativa):**

Esta fase hace referencia a la inyección controlada de 0,1 Mt de CO_2 (100.000 toneladas) durante 3 años a través de un solo pozo de inyección. El CO_2 se asume de una fuente industrial local. Desde un punto de vista práctico —aunque no incluido en el análisis económico— este enfoque logístico (transporte terrestre por carretera) es viable para volúmenes de 30 kt/año y proporciona flexibilidad mientras se valida el rendimiento del almacenamiento. En superficie, se instalará una estación móvil de bombeo y compresión para llevar el CO_2 a condiciones de inyección (fase supercrítica densa, típicamente 80–100 bar y 30 °C). El diseño del pozo piloto contempla un pozo vertical completado en el profundo horizonte del yacimiento salino. Se utilizarán aceros y cementos resistentes al CO_2 para aislar las capas permeables cruzadas, y se instalará un revestimiento de producción de 8 1/2" a lo largo del intervalo del yacimiento, asegurando la integridad frente a la corrosión.

Durante la inyección a baja velocidad (alrededor de 30 kt/año de CO_2), se implementará una monitorización intensiva, desplegando instrumentación avanzada (fibra óptica para monitorización de temperatura y sísmica, sensores de presión en el pozo, etc.). La fase piloto incluye 1 a 2 años iniciales de diseño, permisos y construcción (autorizaciones, ingeniería, perforación), seguidos de 3 años de operaciones de inyección y monitorización. Al finalizar la inyección de prueba, se analizarán los resultados técnicos y el rendimiento medioambiental, tomando la decisión de seguir adelante o abandonar.

- **Fase comercial (escala completa):**

El estudio de la cuenca del Ebro se centra en el almacenamiento, y el diseño y evaluación de captura y transporte están fuera del alcance de este estudio. Sin embargo, tanto las posibilidades de captura como de transporte se han considerado para validar escenarios definidos, identificando fuentes disponibles en la zona y posibles posibilidades de transporte para entregar CO2, en las condiciones requeridas, en la recepción de las instalaciones de inyección. En ese caso, el caso de la Cuenca del Ebro define actividades de exploración, diseño y construcción de instalaciones de inyección, diseño y perforación de pozos inyectores, plan e implementación de MMV, y gestión de sitios de almacenamiento, incluyendo el abandono.

Las fases de exploración, precomercial y comercial se analizan mediante un enfoque probabilístico basado en los resultados del modelo geológico, la simulación dinámica y la evaluación de riesgos. Teniendo en cuenta los datos disponibles y las incertidumbres, el caso comercial se basa en un rango de capacidad estimado de 2 Mt a 35 Mt; con 1 o 2 pozos inyectores; tasa de inyección por pozo entre 0,25 y 0,5 MTPA de CO2, y las instalaciones de inyección alineadas con los volúmenes totales manejados (con un máximo de 1 Mt por año). Se asume que el CO_2 será transportado en fase densa a las instalaciones de inyección. Toda la infraestructura de monitorización implementada durante el piloto se ampliará en esta fase y adaptará a un volumen total inyectado, incluyendo al menos un pozo de observación de los acuíferos superficiales, tomando medidas de agua, suelo y aire previo a la inyección (baseline) e implementando medidas de control durante la inyección tanto a través del pozo (fibra optima y sensores de presión y Temperatura) como mediante redes de control ambiental. Finalmente, una vez agotada la capacidad de almacenamiento utilizable, el/los pozo(s) serán abandonados de forma segura y el sitio entrará en una fase de monitorización a largo plazo tras el cierre (décadas) para confirmar la estabilidad permanente del CO_2 almacenado conforme a la normativa aplicable. En el caso de base, la configuración comercial dependerá de dos pozos de inyección que operan en paralelo del orden de 15 Mt de CO_2 durante 30 años y una tasa de inyección de 0,5 CO_2 MTPA por pozo. Para transportar continuamente medio millón de toneladas de CO_2 al año, se podría construir un gasoducto dedicado desde la planta de captación hasta el lugar de almacenamiento.

5.3.3.1 Captura

El caso de la cuenca del Ebro no incluye la fuente de captura ni el análisis de posibilidades y costes de captura. El CO_2 se asume de una fuente industrial local (hay varios emisores candidatos en la región en una radio de 60 km) y, para todos ellos, se han desarrollado tecnologías capturadas para aplicar. Los costes, el diseño y la calidad del CO2 se asumen en los estándares.

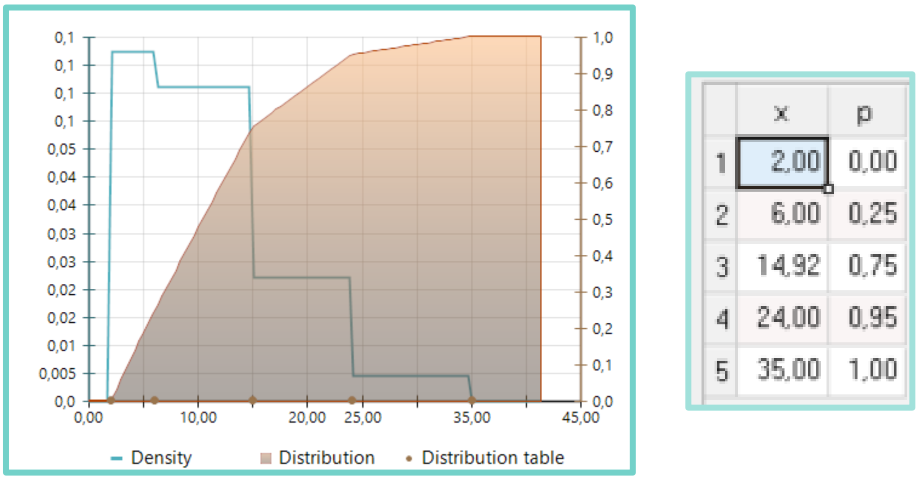
5.3.3.2 Transporte

El caso de la cuenca del Ebro no incluye el análisis de infraestructuras de transporte ni los costes. Para una verificación de viabilidad, se asume que el transporte al sitio durante la fase piloto se realiza mediante camiones cisterna de CO_2 licuado (cada camión transporta aproximadamente 20–25 toneladas, y 3–4 viajes diarios deben alcanzar la tasa de inyección de ~30–35 kt/año). Esta solución es flexible, de bajo coste y adecuada para volúmenes pequeños. En la fase comercial, se prevé por ello un gasoducto dedicado de entre 14 y 30 km, diseñado para operar de forma continua y transportar CO_2 en estado supercrítico. Esta solución garantiza eficiencia, seguridad y escalabilidad, aunque requiere una gran inversión inicial y una planificación detallada.

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

5.3.3.3 Almacenamiento

En base al análisis del modelo geológico, la simulación dinámica y el análisis de riesgos, se define un rango estimado de capacidad en la estructura de Lopín entre 2 Mt y 35 Mt, y se han seleccionado en consecuencia los perfiles de inyección y la gestión del sitio de almacenamiento, asegurando un funcionamiento seguro (la tasa de inyección está limitada por la presión máxima del yacimiento). Para el enfoque probabilístico, la distribución de la capacidad estimada se define de la siguiente manera:



	x	p
1	2,00	0,00
2	6,00	0,25
3	14,92	0,75
4	24,00	0,95
5	35,00	1,00

Figura 5.9: Distribución estimada de la capacidad y distribución acumulada para la estructura de Lopín.

El rango de capacidad compila la posible compartimentación del yacimiento (limitada a 7 Mt); el caso base estudiado y simulado en 3D dinámicamente (cubriendo entre 7 y 15 Mt); y el caso optimista de no compartimentación y evaluado mediante modelado de riesgo 1D (hasta 35 Mt). La presión máxima del yacimiento y el perfil de inyección se han definido específicamente para cada uno de esos rangos y se denominan en este texto como Caso 1, Caso 2 y Caso 3, respectivamente (Table 4.8).

Por ejemplo, en el caso de las 14,9 millones de toneladas, el sitio de operación cubre 30 años a través de dos pozos. El diseño considera inyecciones simultáneas o alternas, con tasas de aproximadamente ~0,25 Mt/año por pozo. Modelos dinámicos actualizados confirman que el yacimiento puede soportar este volumen sin superar el gradiente de fractura (~0,17 bar/m). La sobrepresión máxima prevista es de 60–70 bar en el peor de los casos, con una gestión adaptativa para evitar interferencias entre pozos. La pluma de CO_2 se extiende hasta un radio de hasta 2,5–3 km por pozo, cubriendo hasta 15 km². A largo plazo, el CO_2 queda inmovilizado por disolución y atrapamiento residual. Se prevé un periodo de monitorización posterior a la inyección de al menos 20–30 años, de acuerdo con la Directiva Europea de Almacenamiento Geológico (ASP).

CASO	Capacidad estimada (Mt)	Pozos inyectores (unidades)	Piloto de tasa de inyección de pozo (3 años)	Tasa de inyección de pozo comercial
Caso 1	[2, 7)	1	0,03 MTPA	0,25 MTPA
Caso 2	[7,15)	2	0,03 MTPA	0,25 MTPA
Caso 3	[15, 35]	2	0,03 MTPA	0,50 MTPA

Tabla 5.9 Escenario para el proyecto de CO2 de la cuenca del Ebro

El sistema de monitorización se amplía para incluir una red de pozos de observación, estudios sísmicos 3D periódicos, sensores en profundidad, DAS, InSAR y monitorización geoquímica. También se evalúa la integridad de los pozos heredados y se instala una red sísmica local para detectar microsismicidad inducida.

La duración de la fase comercial depende de la capacidad estimada. El perfil de inyección para los 5Mt, 14,9 Mt y 25 Mt se presenta en la Fig. 5.10.

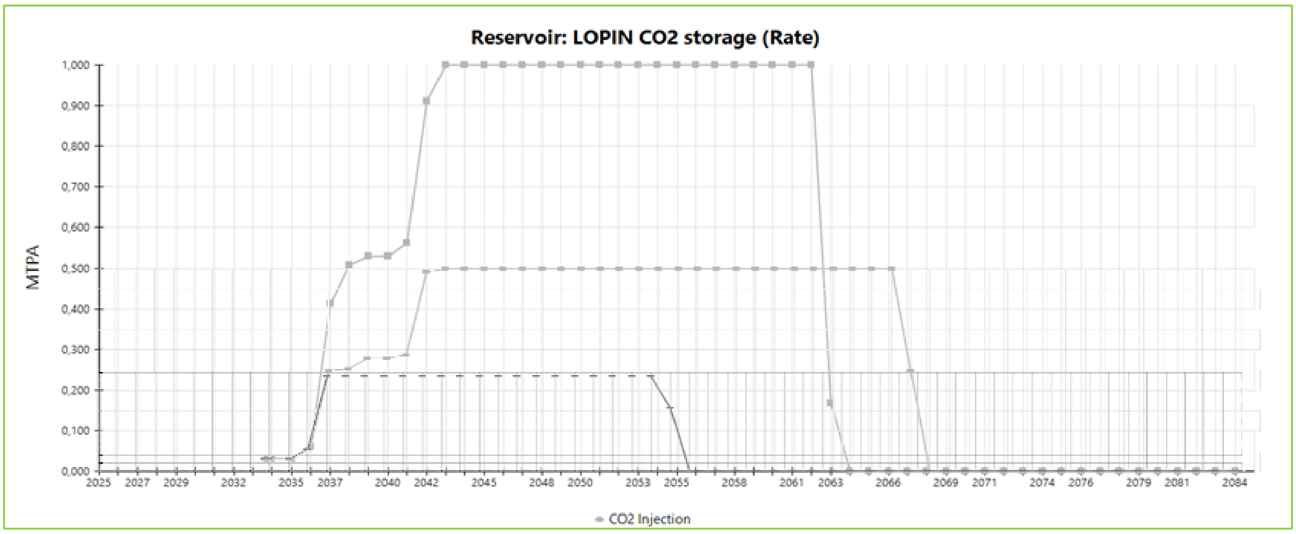


Figura 5.10: Perfiles de inyección de CO2 propuestos para 5 Mt (1 pozo, meseta de 0,25 MTPA), 14,9 Mt (meseta de 2 pozos, meseta de 0,5 MTPA) y 25 Mt (2 pozos, meseta de 1 MTPA) de capacidad estimada para todo el ciclo de vida.

Para el análisis probabilístico del caso de la cuenca del Ebro, se han definido los costes (CAPEX, OPEX, ABEX), tiempos de construcción, dependencias y éxito esperado (Pg, Pe). Los parámetros y distribuciones se muestran en la Fig. 4.11.

5.3.3.4 Plan de Seguimiento (MMV)

El proyecto de la Cuenca del Ebro establece un programa integral de Monitorización, Medición y Verificación (MMV) para garantizar la inyección segura de CO_2 y la contención a largo plazo. Se recoge una línea base sólida antes de las operaciones, incluyendo datos sísmicos 3D y muestras de aguas subterráneas. El pozo de inyección estará instrumentado con sensores permanentes—cables de fibra óptica (para DAS, temperatura y presión) y herramientas de fondo—permitiendo el seguimiento en tiempo real de las condiciones del fondo, sismicidad y evolución del penacho mediante encuestas VSP repetidas. El plan de monitorización de la cuenca del Ebro combina la monitorización directa del pozo, el subsuelo y el entorno superficial, utilizando tecnologías de última generación en línea con las recomendaciones del proyecto. Los datos recogidos serán analizados continuamente y comparados con las predicciones de los modelos. Se definen umbrales claros de alerta y acciones correctivas que aseguran operaciones de almacenamiento seguras. Este enfoque permitirá validar en campo el comportamiento de los yacimientos y garantizar una contención eficaz de CO_2, proporcionando la confianza necesaria antes de escalar el proyecto a la fase comercial.

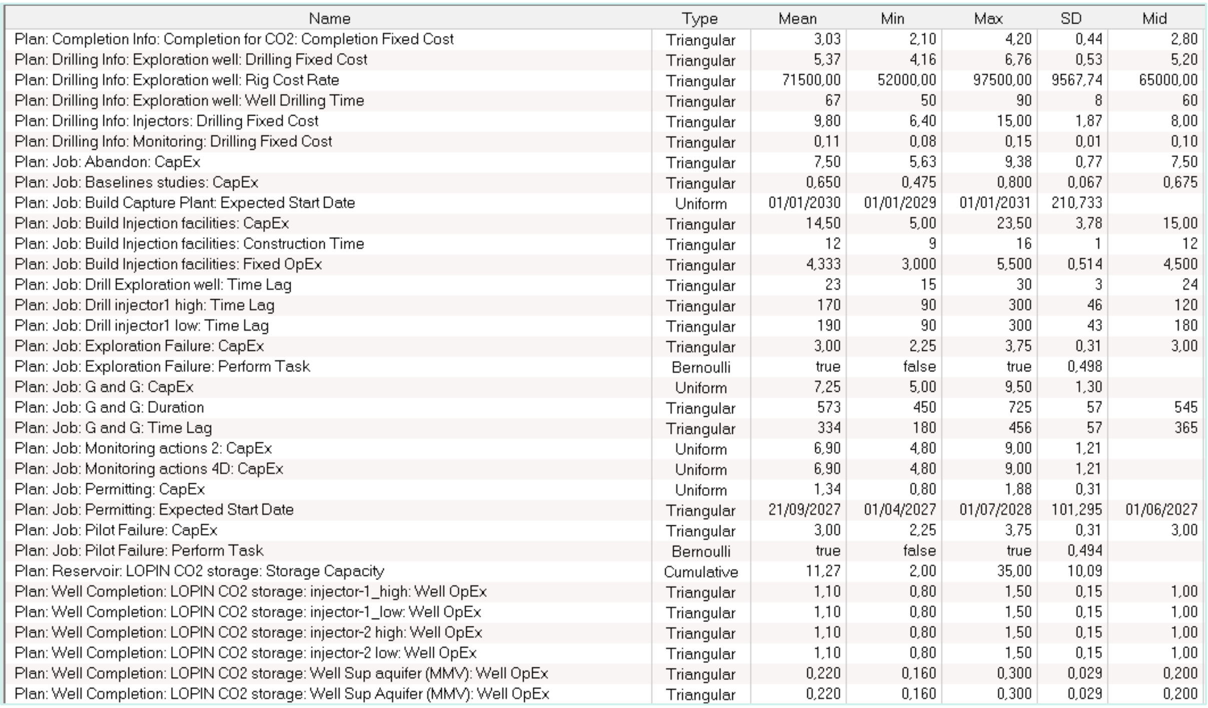
La definición base se establecerá antes de la inyección. Esto incluye la adquisición de datos sísmicos de referencia (e.g. 3D sísmicos) y muestras de aguas subterráneas/subterráneas. Además, el pozo de inyección estará equipado con fibra óptica a lo largo de la tubería e instrumentación en el fondo del pozo.

La gestión de la presión es central en el plan. Se comparará el monitoreo continuo de la presión en la cabeza de pozo y el fondo del pozo con umbrales predefinidos fijados en el 90% de la presión estimada de fractura. Superar estos límites desencadena respuestas operativas como la reducción de las tasas de inyección o la suspensión temporal de la inyección. Debido a fallas cercanas, una red de monitorización microsísmica (fibra óptica, geófonos en fondo o sismómetros superficiales) detectará eventos de pequeña magnitud, con un límite operativo (por ejemplo, M > 2.0) que requiere suspensión inmediata.

La integridad del pozo se verifica mediante registros de unión de cemento tras la perforación y se mantiene mediante pruebas periódicas durante la inyección: comprobaciones de válvulas, pruebas de presión del anillo y monitorización de corrosión. Se planifica un registro final de integridad antes del abandono.

El monitoreo de la pluma de CO_2 se basa principalmente en la VSP de fibra óptica, considerada suficiente dado el radio de migración limitado esperado (< ~2 km). Se puede añadir sísmica 4D en superficie si es necesario. Este enfoque se alinea con las estrategias utilizadas en pilotos anteriores.

El monitoreo ambiental incluye muestreos de referencia y periódicos de aguas subterráneas, suelo y aire superficial, junto con sensores de CO_2 alrededor del sitio. Aunque el riesgo de fuga es bajo debido a la capa de capa del Triásico, estas medidas proporcionan una garantía adicional. El InSAR por satélite puede usarse para detectar una deformación sutil del terreno.



Name	Type	Mean	Min	Max	SD	Mid
Plan: Completion Info: Completion for CO2: Completion Fixed Cost	Triangular	3,03	2,10	4,20	0,44	2,80
Plan: Drilling Info: Exploration well: Drilling Fixed Cost	Triangular	5,37	4,16	6,76	0,53	5,20
Plan: Drilling Info: Exploration well: Rig Cost Rate	Triangular	71500,00	52000,00	97500,00	9567,74	65000,00
Plan: Drilling Info: Exploration well: Well Drilling Time	Triangular	67	50	90	8	60
Plan: Drilling Info: Injectors: Drilling Fixed Cost	Triangular	9,80	6,40	15,00	1,87	8,00
Plan: Drilling Info: Monitoring: Drilling Fixed Cost	Triangular	0,11	0,08	0,15	0,01	0,10
Plan: Job: Abandon: CapEx	Triangular	7,50	5,63	9,38	0,77	7,50
Plan: Job: Baselines studies: CapEx	Triangular	0,650	0,475	0,800	0,067	0,675
Plan: Job: Build Capture Plant: Expected Start Date	Uniform	01/01/2030	01/01/2029	01/01/2031	210,733	
Plan: Job: Build Injection facilities: CapEx	Triangular	14,50	5,00	23,50	3,78	15,00
Plan: Job: Build Injection facilities: Construction Time	Triangular	12	9	16	1	12
Plan: Job: Build Injection facilities: Fixed OpEx	Triangular	4,333	3,000	5,500	0,514	4,500
Plan: Job: Drill Exploration well: Time Lag	Triangular	23	15	30	3	24
Plan: Job: Drill injector1 high: Time Lag	Triangular	170	90	300	46	120
Plan: Job: Drill injector1 low: Time Lag	Triangular	190	90	300	43	180
Plan: Job: Exploration Failure: CapEx	Triangular	3,00	2,25	3,75	0,31	3,00
Plan: Job: Exploration Failure: Perform Task	Bernoulli	true	false	true	0,498	
Plan: Job: G and G: CapEx	Uniform	7,25	5,00	9,50	1,30	
Plan: Job: G and G: Duration	Triangular	573	450	725	57	545
Plan: Job: G and G: Time Lag	Triangular	334	180	456	57	365
Plan: Job: Monitoring actions 2: CapEx	Uniform	6,90	4,80	9,00	1,21	
Plan: Job: Monitoring actions 4D: CapEx	Uniform	6,90	4,80	9,00	1,21	
Plan: Job: Permitting: CapEx	Uniform	1,34	0,80	1,88	0,31	
Plan: Job: Permitting: Expected Start Date	Triangular	21/09/2027	01/04/2027	01/07/2028	101,295	01/06/2027
Plan: Job: Pilot Failure: CapEx	Triangular	3,00	2,25	3,75	0,31	3,00
Plan: Job: Pilot Failure: Perform Task	Bernoulli	true	false	true	0,494	
Plan: Reservoir: LOPIN CO2 storage: Storage Capacity	Cumulative	11,27	2,00	35,00	10,09	
Plan: Well Completion: LOPIN CO2 storage: injector-1_high: Well OpEx	Triangular	1,10	0,80	1,50	0,15	1,00
Plan: Well Completion: LOPIN CO2 storage: injector-1_low: Well OpEx	Triangular	1,10	0,80	1,50	0,15	1,00
Plan: Well Completion: LOPIN CO2 storage: injector-2 high: Well OpEx	Triangular	1,10	0,80	1,50	0,15	1,00
Plan: Well Completion: LOPIN CO2 storage: injector-2 low: Well OpEx	Triangular	1,10	0,80	1,50	0,15	1,00
Plan: Well Completion: LOPIN CO2 storage: Well Sup aquifer (MMV): Well OpEx	Triangular	0,220	0,160	0,300	0,029	0,200
Plan: Well Completion: LOPIN CO2 storage: Well Sup Aquifer (MMV): Well OpEx	Triangular	0,220	0,160	0,300	0,029	0,200

Figura 5.116: Distribución definida para CAPEX, OPEX y tiempos de construcción seleccionados

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

5.3.4 Planificación propuesta

La hoja de ruta del proyecto en la cuenca del Ebro se ha concebido de forma gradual, comenzando con la fase de exploración, un piloto de demostración y, si tiene éxito, evolucionando hacia un despliegue comercial a mayor escala. La duración clave de las actividades se ha definido en un rango temporal para evaluar el impacto de posibles retrasos en las actividades en curso, es decir, en el caso de concesiones de permisos de exploración, estudios sísmicos, construcción de instalaciones de inyección o retrasos en la perforación.

Las fases planificadas se describen a continuación, incluyendo sus duraciones estimadas, actividades clave y consideraciones logísticas y regulatorias:

- **Fase de exploración y caracterización (entre 4 y 6 años):**

El proyecto comienza en 2027 con la solicitud de permiso de exploración y se obtiene entre 12 y 18 meses después. La fase de exploración comienza con estudios subterráneos detallados. El plan incluye la adquisición de nuevos datos sísmicos de reflexión de alta resolución en la zona de Lopín, así como estudios geoquímicos y geomecánicos basados en laboratorio (Lachen et al., 2025). Un hito crítico será la perforación de un pozo exploratorio en el lugar propuesto y las pruebas de inyección. Durante esta fase se recopilarán datos clave de la formación de almacenamiento (porosidad, permeabilidad, presión inicial, espesor) y de la roca captable, reduciendo así las incertidumbres en el modelo geológico. Paralelamente, se iniciarán procedimientos regulatorios, incluyendo la evaluación del impacto ambiental del proyecto piloto, consultas con las autoridades y las comunidades locales (por ejemplo, para asegurar la aceptación social) y la preparación de la solicitud de un permiso temporal de almacenamiento para el piloto (Canteli et al., 2025). Cabe señalar que aún no se ha seleccionado ningún emisor industrial específico como fuente de CO_2; por lo tanto, durante esta fase también tendrán lugar negociaciones para el suministro de CO_2 para el piloto (por ejemplo, posibles acuerdos con plantas regionales de cemento o química).

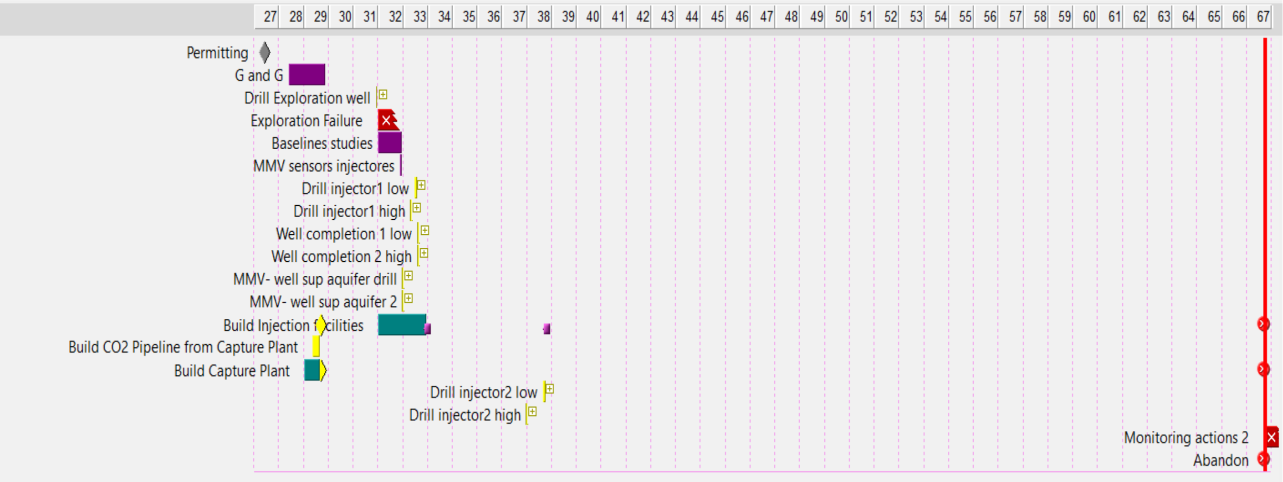


Figura 5.127: Calendario de actividades para la evaluación completa del ciclo de vida

- **Fase piloto de inyección (3 años):**

Una vez que la caracterización del sitio haya sido completada satisfactoriamente y nuevos datos validen la viabilidad geológica de la estructura Lopin, y se soliciten y obtengan permisos piloto (de investigación) para explotación, comenzará el diseño y construcción de instalaciones piloto. La actividad de datos de referencia se realiza durante al menos 1 año. Se perfora y completa un nuevo pozo inyector (instalación de tubos de inyección, cabeza de pozo con válvulas de seguridad y líneas de flujo), así como el despliegue de la infraestructura superficial requerida, incluyendo la unidad de compresión y planta de inyección, sistemas de suministro eléctrico, tanques y tuberías de conexión, y equipos de monitorización superficial (Lachen et al., 2025, D4.5). Durante esta fase, se espera que se inyecte un volumen total de 100.000 toneladas de CO_2 comprimido en el yacimiento durante aproximadamente tres años de operación piloto. El propósito de este piloto es doble: demostrar la viabilidad técnica (inyectividad y capacidad de almacenamiento) y recopilar datos de campo real para calibrar los modelos. Según simulaciones dinámicas actualizadas, el pozo piloto CCS-1 podría inyectar aproximadamente 0,03–0,05 Mt/año sin superar los límites de presión seguros, lo que corresponde a ~0,1 Mt durante tres años, respetando el límite operativo (≈90 bar de sobrepresión) definido por la integridad del caprock (Ron et al., 2026). Durante esta fase, el plan MMV se implementará completamente, con monitorización en tiempo real de la respuesta del embalse. Es importante señalar que, para suministrar esta inyección piloto, el plan logístico transporta CO_2 mediante camiones cisterna criogénicos desde una fuente emisora cercana hasta el lugar del pozo, dados los volúmenes relativamente bajos y las distancias manejables. Esta solución flexible permite que las operaciones piloto comiencen sin necesidad de infraestructura de transporte dedicada a larga distancia.

- **Evaluación y toma de decisiones intermedias (después del periodo piloto):**

Tras la finalización de la inyección piloto (3 años), el proyecto entra en un periodo de análisis exhaustivo de resultados. Los equipos técnicos compararán los datos observados (presiones de los yacimientos, migración de la columna de CO_2, eventos microsísmicos, etc.) con predicciones previas. Si el rendimiento del almacenamiento es favorable —es decir, confirmando buena inyectividad, ausencia de fugas y sismicidad controlada— el proyecto avanzará para planificar una expansión a escala comercial. Esto implicará la preparación de un informe de Decisión Final de Inversión (FID) que consolide los aprendizajes del piloto, una evaluación económica y financiera actualizada (Canteli et al., 2025, D4.9) y un plan detallado para la siguiente fase. En esta etapa intermedia, también se perseguirá la concesión de almacenamiento geológico a escala comercial, lo que requerirá la expansión o adaptación de los permisos existentes para cubrir volúmenes mayores y periodos de inyección más largos (probablemente incluyendo una nueva Declaración de Impacto Ambiental para la fase industrial de 30 años). Basándose en experiencias similares, se estima un plazo de aproximadamente dos años para asegurar las autorizaciones y la financiación para la fase comercial posterior al piloto. Durante este periodo, el pozo piloto puede permanecer bajo observación (sin más inyección de CO_2), mientras continúa con el monitoreo inicial posterior a la inyección para extender los conjuntos de datos de caída de presión y evolución de la pluma.

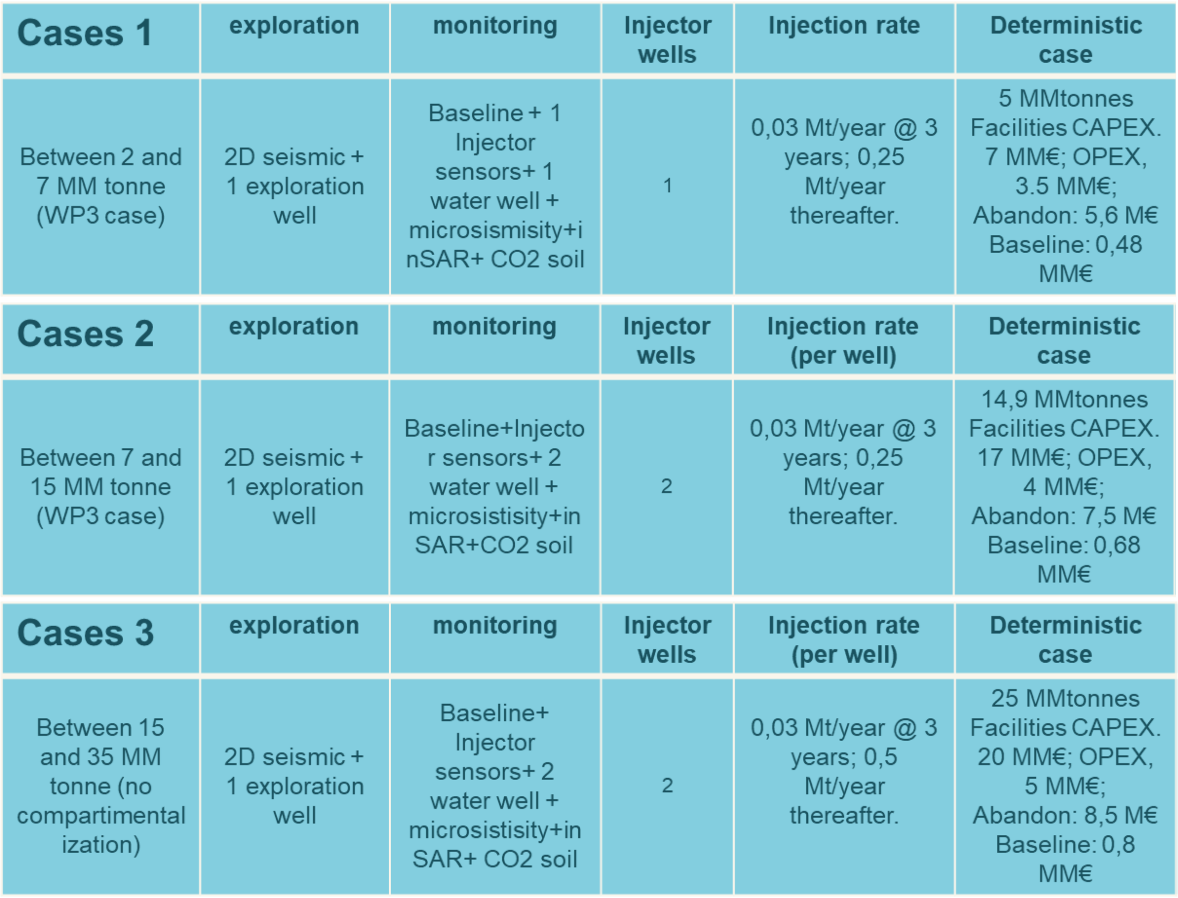
Para el enfoque probabilístico y basado en la evaluación del experto del equipo, se han considerado la probabilidad de éxito de la exploración (Pg, es decir, la probabilidad de obtener resultados positivos durante la fase de exploración y avanzar con la construcción del piloto) y la probabilidad de éxito del piloto (Pe, es decir, la probabilidad de explotación tras verificar el comportamiento del complejo de almacenamiento apropiado durante las pruebas piloto) como se indica en la Tabla 5.13. para (1) asumiendo éxito geológico y de pilotos; (2) incluyendo la probabilidad geológica de éxito y el correspondiente porcentaje de desarrollos abandonados tras los resultados de los pozos de exploración; y (3) incluyendo el cambio geológico de éxito y, para quienes pasan al desarrollo piloto, aplicaron Pe como porcentaje de no haber casos abandonados tras analizar los resultados del comportamiento piloto.

Caso probabilístico estudiado	Pg	Pe
Caso de éxito	1	1
Impacto en el éxito geológico	0.6	1
Impacto geológico y en el éxito de los pilotos	0.54	0.46

Tabla 5.13 Se consideraron los valores de probabilidad de éxito geológico (Pg) y probabilidad de éxito del piloto (Pe) para los 3 escenarios probabilísticos analizados.

- **Fase comercial a gran escala (hasta su abandono):**

Una vez tomada la decisión de ampliar el proyecto, el plan prevé el despliegue de uno o dos pozos de inyección, junto con la ampliación de las instalaciones superficiales. El desarrollo comercial se define según las bases de capacidad estimadas, así como el plan MMV requerido.



Cases 1	exploration	monitoring	Injector wells	Injection rate	Deterministic case
Between 2 and 7 MM tonne (WP3 case)	2D seismic + 1 exploration well	Baseline + 1 Injector sensors+ 1 water well + microsismisity+inSAR+ CO2 soil	1	0,03 Mt/year @ 3 years; 0,25 Mt/year thereafter.	5 MMtonnes Facilities CAPEX. 7 MM€; OPEX, 3.5 MM€; Abandon: 5,6 M€ Baseline: 0,48 MM€

Cases 2	exploration	monitoring	Injector wells	Injection rate (per well)	Deterministic case
Between 7 and 15 MM tonne (WP3 case)	2D seismic + 1 exploration well	Baseline+Injector sensors+ 2 water well + microsistisity+inSAR+CO2 soil	2	0,03 Mt/year @ 3 years; 0,25 Mt/year thereafter.	14,9 MMtonnes Facilities CAPEX. 17 MM€; OPEX, 4 MM€; Abandon: 7,5 M€ Baseline: 0,68 MM€

Cases 3	exploration	monitoring	Injector wells	Injection rate (per well)	Deterministic case
Between 15 and 35 MM tonne (no compartimentalization)	2D seismic + 1 exploration well	Baseline+ Injector sensors+ 2 water well + microsistisity+inSAR+ CO2 soil	2	0,03 Mt/year @ 3 years; 0,5 Mt/year thereafter.	25 MMtonnes Facilities CAPEX. 20 MM€; OPEX, 5 MM€; Abandon: 8,5 M€ Baseline: 0,8 MM€

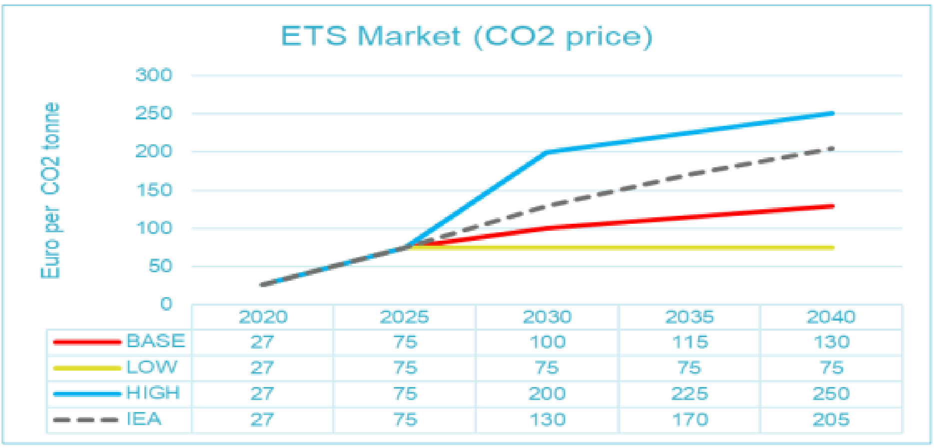
Figura 5.14: Descripción de los casos para la capacidad estimada de 5 Mt, 14,9 Mt y 25 Mt de Lopin para la evaluación determinista

5.3.5 Evaluación económica

La evaluación económica del caso de la cuenca del Ebro ha seguido tanto un enfoque determinista como probabilístico utilizando el software PetroVR y basado en:

- Definición de la distribución estimada de capacidad, basada en incertidumbres geológicas y posibilidad de compartimentación. Se ha considerado un rango entre 2 Mt y 35 Mt con P75 = 14,9 Mt. La evaluación determinista se basa en 5 Mt, 14,9 Mt y 25 Mt.

- Definición de fase de exploración: campañas geológicas y geofísicas, y pozo y prueba de exploración.
- Definición de pozo(s) y perfiles de inyección, para la fase piloto (1 pozo, 0,03 MTPA durante 3 años) y para la fase comercial (tabla XX). Costes de pozo incluyendo perforación y completación).
- Definición de las instalaciones de inyección: planta de captura y transporte quedan fuera del estudio. Las instalaciones de superficie (recepción, compresor e inyectores) se definen en función de los volúmenes máximos de CO2 manejados.
- Horario (o planificación): las diferentes actividades realizadas en el tiempo, considerando la dependencia entre actividades. La incertidumbre (retrasos, avances) se incluye para actividades clave (proceso de permisos, tiempo de perforación, construcción de instalaciones) según la distribución del tiempo requerida. Las actividades consideradas son la solicitud y concesión de permisos de exploración, la fase de exploración, las mediciones de línea base, la perforación y los pozos de completación, la construcción de instalaciones de inyección, la solicitud del plan MMV y el abandono cuando se alcanza el 95% de la capacidad total estimada.
- Probabilidad de éxito geológico (Pg) y probabilidad de éxito de explotación (Pe): para el enfoque probabilístico, se aplica una probabilidad de éxito geológico Pg=0,6% (es decir, tras la exploración del pozo, el 60% de los casos pasan a la siguiente fase y el 40% se abandona el proyecto); y tras la fase piloto, se aplica un cambio de éxito de explotación de Pe=0,54% (es decir, tras 3 años de operación piloto, el 54% de los casos pasan a la fase comercial y el 36% del proyecto se abandona). Pg y Pe se han definido basándose en información existente y en la definición de paneles internos de expertos.
- Modelo económico: Se basa en un modelo de flujo de caja económico, donde se asume que los ingresos corresponden al valor de toneladas de CO2 almacenadas al año al precio del ETS de la UE.
- Se han asumido previsiones de precios (base, mínimo y máximo). Otros parámetros financieros de interés son el tipo de descuento (9%) y la inflación (2,2%). Los resultados se descuentan hasta 2025.



	2020	2025	2030	2035	2040
BASE	27	75	100	115	130
LOW	27	75	75	75	75
HIGH	27	75	200	225	250
IEA	27	75	130	170	205

Figura 5.15: Precios de previsión de CO2 ETS (Base, Máximo y Mínimo)

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

- Los costes (CAPEX y OPEX) se han definido como Clase IV en 2025 y, para la definición de distribución, se han considerado la distribución triangular con el coste real en 2025 como punto central (-20%, +30%).
- Resultados deterministas: se indican para una capacidad estimada de 5 Mt, 14,9 Mt; y 25 Mt.
- Resultados probabilísticos: Montecarlo con 10.000 simulaciones por 5.000 para criterios comparativos.
- Se ha realizado un análisis de sensibilidad a las distribuciones de la capacidad; un porcentaje que se reciba por tonelada (tarifa de almacenamiento).

Los **resultados deterministas** para 5 Mt, 14,9 Mt y 25 Mt para las 3 previsiones de precios definidas muestran valores positivos para el VPN (2025, 9%) en todos los casos asumiendo el precio del ETS de CO2 por 1 tonelada de CO2 inyectado, con inversiones entre 65 M€ y 105 M€, y un flujo de caja máximo entre 37 M€ y 64 M€ dependiendo de la capacidad de almacenamiento considerada. Sin embargo, también se ha calculado el punto de equilibrio (breakeven) del precio del CO_2 para los 3 casos deterministas, lo que da un 73 €/tonelada si es 5 Mt de capacidad estimada; 42 €/tonelada si es 14,9 Mt de capacidad estimada, y 27 €/tonelada si es 25 Mt de capacidad estimada. La inversión total para el desarrollo del sitio de almacenamiento (piloto y comercial) se estima entre 65 y 105 millones de euros (precios de 2025). (Tabla 5.10).

Caso	CAPEX (Millón€)	OPEX (Millón€)	Máximo de retiro de efectivo (Millón de euros)	NPV (9, 2025, BP) (Millón de euros)	NPV (9, 2025, LP) (Millón de euros)	NPV (9, 2025, HP) (Millón de euros)	Breakeven (€/tonelada)
5 Mt	65	135	-37	82	16	165	73
14,9 Mt	99	275	-49	178	51	337	42
25 Mt	105	280	-64	382	143	690	27

Tabla 5.10 Resultados deterministas para la capacidad estimada de 5 Mt, 14,9 Mt y 25 Mt

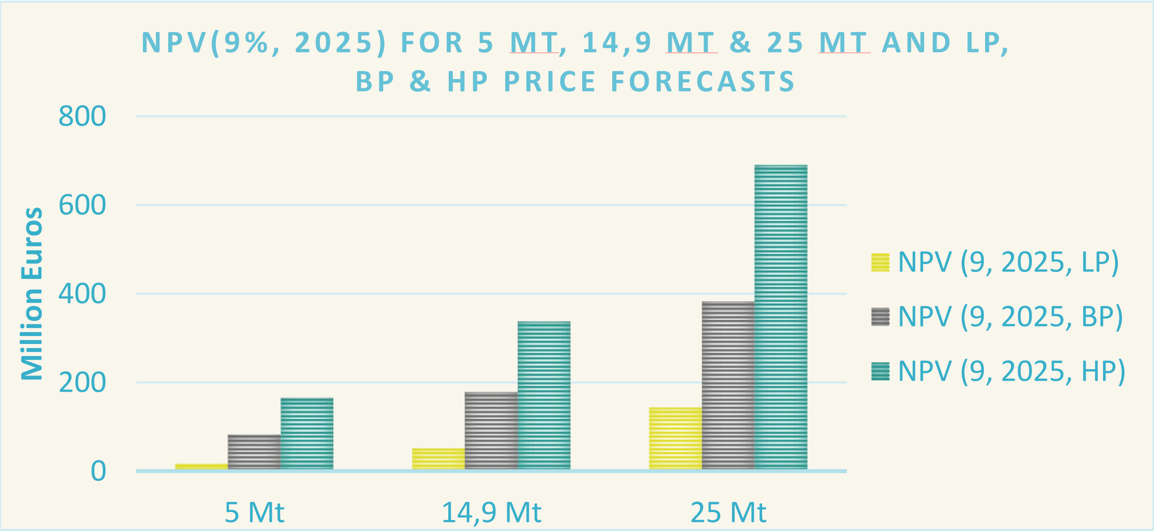


Figura 5.16: VPN (9%, 2025) para 5 casos deterministas Mt, 14,9 Mt y 25 Mt

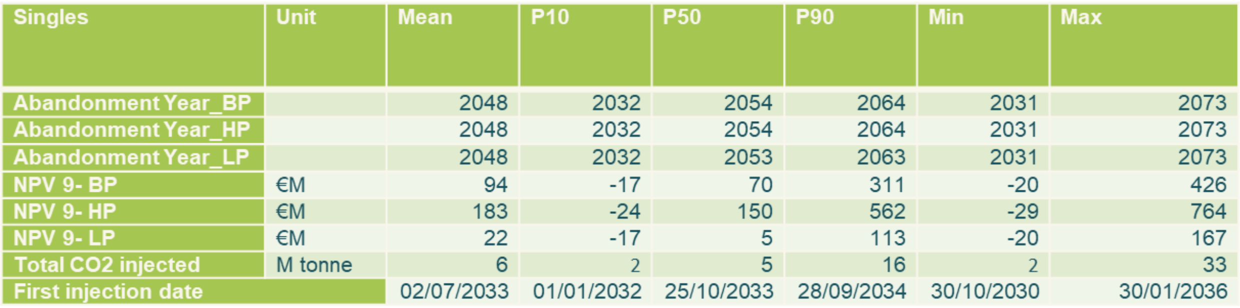
Según el **análisis probabilístico**, se han analizado los casos: (1) Considerando el caso de éxito (es decir, Pg=1 y Pe=1); (2) considerando Pg=0,6 y Pe=1; y (2) considerando Pg=0,54 & Pg=0,46. Todos los casos han sido análisis para todo el ciclo de vida y la definición de distribuciones de parámetros para elementos clave en CAPEX, OPEX y temporización (tabla 4.11). Los resultados se muestran en las Tablas 5.11, 5.12 y 5.13, respectivamente.

En el primer caso (1) en el que todas las evaluaciones iniciales se basan en exploración, fase piloto y comercial, los resultados sobre el VP para todos los precios considerados son positivos (excepto la historia muy baja del precio bajo, <P10), lo que ofrece una muy buena visión general de un caso sólido. Sin embargo, debe considerarse que la suposición de dar el precio de almacenamiento por tonelada de ETS es solo para una referencia común y, para una evaluación de caso de negocio, el precio de ETS por tonelada debe cubrir las fases de captura, transporte y almacenamiento.

Individuales (Pg = 1; Pe=1)	Unidad	Promedio	P10	P50	P90	Min	Max
Año de abandono BP		2058	2051	2057	2065	2044	2073
Año de abandono HP		2058	2051	2057	2065	2044	2073
Abandonment Year LP		2058	2051	2058	2064	2044	2073
Resultados: NPV 9- TA	M€	168	59	144	327	25	428
Resultados: NPV 9- HP	M€	319	128	283	592	66	773
Resultados: NPV 9- PL	M€	47	2	32	122	-11	165
Volúmenes: CO2 total inyectado	Millones de toneladas	11	4	10	17	2	33

Tabla 5.114 Resultados del NPV (9%, 2025) y del año de abandono para la previsión de precios de 3 CO2 (BP, LP, HP) y el caso de éxito (Pg=1 & Pe=1) basados en análisis probabilístico.

En el segundo caso (2), los resultados económicos probabilísticos para todo el ciclo de vida y basados en el precio base que evalúa el éxito geológico (Pg=0,6 & Pe=1), la distribución acumulada muestra un P50 de 70 MM€ (valor medio de 94 M€) con valores negativos en el lado bajo de la distribución (P<15%). Se obtienen resultados similares en el caso de precios altos, aunque, en el caso de precio bajo, hay un 48% de probabilidad de NPV negativo (tabla 4.10). En conclusión, solo para el valor de la base (<p20) de los 3 precios considerados son negativos, lo que da, de nuevo, resultados muy positivos y con la misma suposición de precios ETS mencionada antes.



Singles	Unit	Mean	P10	P50	P90	Min	Max
Abandonment Year_BP		2048	2032	2054	2064	2031	2073
Abandonment Year_HP		2048	2032	2054	2064	2031	2073
Abandonment Year_LP		2048	2032	2053	2063	2031	2073
NPV 9- BP	€M	94	-17	70	311	-20	426
NPV 9- HP	€M	183	-24	150	562	-29	764
NPV 9- LP	€M	22	-17	5	113	-20	167
Total CO2 injected	M tonne	6	2	5	16	2	33
First injection date		02/07/2033	01/01/2032	25/10/2033	28/09/2034	30/10/2030	30/01/2036

Tabla 5.12 Resultados del NPV (9%, 2025) y del año de abandono para los 3 precios de CO2 pronosticados (BP, LP, HP) y Pg=0,6 & Pp=1 basados en análisis probabilístico.

También se ha analizado el impacto de la fecha de la primera inyección (retrasos y permisos de aceleración, construcción, entregas, ...). Si los casos deterministas definen la fecha esperada de la primera inyección en 2033, considerando el impacto de diferentes eventos, se puede esperar un rango de 6 años, con un impacto estimado de una reducción del 10% del valor del VN por un retraso de 1 año solo debido al proceso de permisos. (Fig. 4.8)

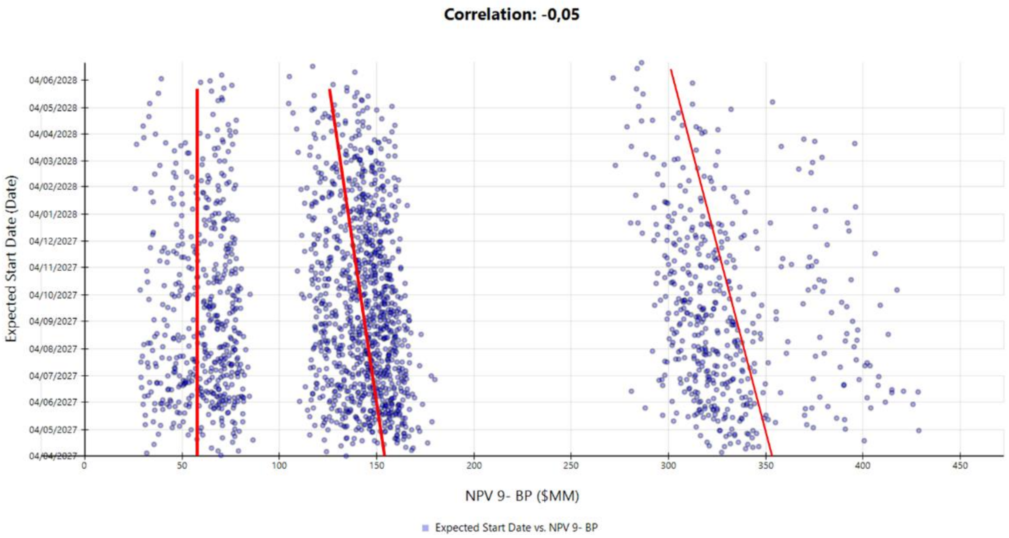


Figura 5.17: Impacto en el retraso en la obtención de permisos sobre el NPV (9%, 2025)

Finalmente, los resultados que consideran tanto Pg=0,54 como Pe=0,46 (3) aportan mayor claridad sobre el impacto de las incertidumbres geológicas y operativas, respectivamente. Estas probabilidades se han obtenido mediante una evaluación interna de expertos. En ese caso, con estos casos combinados de fallos, para todos los precios de previsión los resultados son negativos para <P50- sin embargo, los resultados de riesgo esperados en al menos el 50% de los casos y para los 3 precios de previsión son muy altos (NPV (9%, 2025, BP)>300 millones de euros), lo que podría considerarse un buen resultado que invita a pensar en el siguiente paso.

Pg=0,54; Pe=0,42	Unidad	Promedio	P10	P50	P90	Min	Max
Abandono Year_BP		2039	2030	2036	2059	2030	2072
Abandono Year_HP		2039	2030	2033	2059	2030	2072
Abandono Year_LP		2039	2030	2034	2059	2030	2071
NPV 9- BP	M€	36	-21	-16	185	-25	463
NPV 9- HP	M€	76	-26	-8	331	-32	796
NPV 9- LP	M€	10	-23	-6	68	-27	207
CO2 total inyectado	Mtonne	3	0	5	16	0	33

Tabla 5.135 Resultados del año de abandono de la VPN (2025,9) para los 3 precios de CO2 pronosticados (BP, LP, HP) y Pg=0,54 & Pp=0,46 basados en análisis probabilístico.

5.3.6 Evaluación social y ambiental

Lopín debe entenderse como un caso de aceptación social condicional, sin un apoyo o rechazo claro. La evidencia de la cuenca del Ebro muestra que la aceptación dependería principalmente de si el proyecto se percibe como seguro, territorialmente justo, transparente y beneficioso para la zona anfitriona. Un tema central es que Lopín está lejos de ser un gran emisor de CO_2 —en el sentido de que no se perciben beneficios directos en estas zonas—, lo que inmediatamente genera preocupaciones sobre la justicia territorial: las comunidades locales pueden cuestionar por qué una zona rural escasamente poblada debería asumir los riesgos y cargas de almacenar emisiones producidas en otros lugares. En este contexto, el proyecto se evalúa mediante una lógica pragmática de coste-beneficio en la que la promesa del desarrollo local debe superar claramente los riesgos percibidos y la desconfianza histórica de la zona hacia los proyectos energéticos impulsados por externas.

Las principales preocupaciones identificadas para Lopín se refieren a posibles fugas, contaminación por acuíferos, sismicidad inducida, riesgos relacionados con el transporte, impactos medioambientales y agrícolas, así como el coste global y la credibilidad a largo plazo del proyecto. Estas preocupaciones se ven reforzadas por la percepción de que el CCS podría convertirse en una excusa para retrasar reducciones más profundas de emisiones y por el temor a que la zona pueda convertirse en una "aldea experimental" para CO_2 no local. Al mismo tiempo, los residentes y partes interesadas identifican posibles beneficios, especialmente la creación de empleo, la retención de la población, mejoras en infraestructuras, rendimientos fiscales, atracción de empresas y una revitalización económica más amplia. Sin embargo, estos beneficios esperados no se dan por sentados: solo se consideran creíbles si son específicos, visibles, verificables y distribuidos de forma justa.

Un hallazgo recurrente es que la información, la transparencia y el compromiso temprano no son tareas secundarias de comunicación, sino condiciones propicias para la legitimidad del proyecto. Debido a que el conocimiento de CCS ha sido escaso, el compromiso en las primeras etapas ofrece la oportunidad de moldear percepciones antes de que las posiciones se endurezcan, pero solo si el proceso se percibe como genuino y no meramente consultivo. En todas las actividades españolas, los participantes exigieron información continua, explicaciones técnicas accesibles, transparencia respecto a permisos, inspecciones, participación en beneficios y riesgos, y mecanismos de supervisión local, incluyendo comités ciudadanos, auditorías independientes y, en algunos casos, veto o fuertes derechos de participación local. La transparencia declarada sin la voz ciudadana no se consideraba creíble.

Esto también apunta a posibles riesgos de disputa local. La oposición podría intensificarse si el proyecto se percibe como impuesto desde fuera, si el proceso de concesión de permisos es opaco, si los beneficios permanecen vagos o retrasados, o si las comunidades sienten que se les vuelve a pedir que acojan infraestructuras que sirvan principalmente a actores externos. Las experiencias previas de promesas incumplidas en proyectos renovables e infraestructurales han creado un legado de desconfianza que puede reactivar fácilmente las críticas a menos que el proyecto incluya garantías vinculantes, cláusulas de cumplimiento, sanciones por incumplimiento y verificación independiente. En términos prácticos, la falta de beneficios locales percibidos es en sí misma un riesgo importante para el proyecto.

Para la obtención de permisos de proyecto, la comunicación y el diseño, la implicación es que el concepto de Lopín debe incorporar los requisitos sociales desde el principio. Esto implica una evaluación rigurosa y accesible del impacto ambiental; explicación clara de las medidas de seguridad, la supervisión y los arreglos de transporte; procesos administrativos y de permisos transparentes; monitorización independiente y auditorías externas; y un paquete concreto de beneficios locales vinculado a prioridades comunitarias como empleo, formación, infraestructuras, servicios públicos y desarrollo regional. La comunicación no debe basarse únicamente en argumentos genéricos sobre el clima, sino que debe explicar por qué se está considerando Lopín, por qué el CCS está justificado en este caso, cuáles son los beneficios locales, cuáles son los límites y riesgos, y cómo la comunidad mantendrá la supervisión durante todo el ciclo de vida del proyecto. En resumen, la viabilidad de Lopín dependerá no solo de la solidez técnica y económica, sino de si el proyecto puede demostrar de forma creíble seguridad, equidad, transparencia y valor tangible para el territorio.

Desde un punto de vista ambiental, los núcleos de población más cercanos a la zona de interés son Codo, a 3 km al norte; Belchite, a 3,8 km al oeste; Almonacid de la Cuba, a 7,7 km al suroeste, Letux a 9,4 km al suroeste; y Lécera y Vinaceite, a 10 km al south y sureste, respectivamente. En cuanto a la

Red Natura 2000, las zonas más cercanas son la SCI (ES2430091) "Llanuras y estepas de la margen derecha del Ebro" y la SPA (ES0000136) "Estepas de Belchite-El Planerón-La Lomaza", ambas a unos 4 km al norte de la zona de interés. No se espera ningún impacto en el patrimonio geológico, ya que el LIG más cercano (IB069. Sucesión del Jurásico Inferior y Medio de Belchite-Almonácido de la Cuba) a más de 5 km del proyecto. El estudio hidrogeológico confirma que no existe un curso de agua superficial natural permanente, ni se han identificado cursos temporales notables. No se espera ningún impacto en los hábitats de interés comunitario (HIC). Según la EIA aprobada en esta zona, se esperan medidas adicionales de protección para la avifauna al *Cernícalo Primilla* (Falco naumanni). En general, las condiciones ambientales están bien estudiadas, no se identifican obstáculos, y se esperan medidas preventivas durante la fase de construcción y operación que podrían incluirse fácilmente en el diseño de las instalaciones.

5.3.7 Evaluación de riesgos y beneficios

Aquí se presentan análisis SWOT para subrayar las fortalezas y debilidades del proyecto propuesto.

Fortalezas	**Debilidades**
• Geología regional bien conocida y uniforme • Estructura de almacenamiento probada y caprock regional • Sismicidad natural muy baja • Zona despoblada • Gobierno Regional con experiencia en almacenes de CO2 • Ciudadanos abiertos al desarrollo de CCS	• Pocos y antiguos datos subterráneos • No hay ningún estudio sísmico que cubra la zona • Posible compartimentación • Incertidumbre sobre la fuente de CO2 y el coste de compra del piloto
Oportunidades	**Amenazas**
5. Desarrollar la industria local 6. Potencial de captura directa de aire (energía extraíble) 7. Desarrollo posible con la Comunidad 8. Proximidad a la zona industrial regional	• Momento de solicitud de licencia de exploración • Incertidumbre en el apoyo nacional a la política de la CCS • Acceso incierto a fondos de la UE/nacionales para el piloto

Tabla 5.67 - Análisis DAFO del proyecto de CO2 de la cuenca del Ebro

5.3.8 Conclusiones

Las recomendaciones para el siguiente paso se abordan para reducir las incertidumbres geológicas, es decir, sísmicos para definir con más detalle el potencial de compartimentación, reevaluar el frente de presión mediante la mejora de las características petrofísicas y revisar la capacidad estimada. El impacto de esta información en el PG y el PP reducirá el alcance de los resultados económicos y mejorará las bases para una decisión de retención.

Paralelamente, debería estudiarse las fuentes potenciales de CO2 —incluida la implementación de DACs— para comprender mejor los casos de negocio aplicables.

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