Deliverable 4.6

Permit Dossier: Operations, logistics and well maintenance plans description, Well permits road map, MMV plan and HSE, emergency response and well containment plans.

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

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2. Executive summary

Within WP4 of PilotSTRATEGY, consortium partners developed an optimized CO_2 geological storage pilot ensuring technical robustness, economic feasibility, and full HSE compliance, integrating best practices from previous European CCS initiatives.

The pilot scheme comprises four main components: **Well design; Capture, Transport and Facilities layout; Project Risk Assessment; and Monitoring Strategy (MMV).** Key results are documented across WP4 deliverables, including technical, economic, and regulatory outputs

This report – Deliverable D4.6 – focuses on the permitting dossier, covering legal requirements, operational plans, HSE, MMV, and emergency procedures. It includes case studies for the Paris, Ebro, and Lusitanian basins, plus regulatory overviews for Poland and Greece.

1. Paris Basin (France)

The French case study addresses a pilot-scale CO_2 injection project in the Paris Basin using a near-site industrial emitter producing high-purity CO_2 (300 kt/y), with a total injection limit of 100 kt. Four development scenarios were defined, combining onsite/offsite well locations and local/external CO_2 sources, including transport by rail, ensuring consistent CO_2 conditions at the plant boundary.

Two **well designs** (standard and long-deviated J profiles) were developed and optimized with updated logging and testing programs. Permitting is expected to take approximately two years under French regulations, followed by up to three years for construction. Procurement of long-lead equipment (casing, compressors, rigs) is a key scheduling factor. **Injection operations** are planned for a short duration of around three months. Prior to injection, brine injectivity tests will be conducted to confirm reservoir performance. Simulations indicate testing durations between 10 and 45 days, with costs of €192k–€738k. Well integrity is ensured through logging, testing, and monitoring, with estimated logging costs: €0.85M–€1.62M for the offsite well and €1.38M–€2.84M for the onsite well.

Two **infrastructure configurations** are defined: a main scenario with a 3 km pipeline and an alternate scenario without pipeline. CO_2 transport by rail requires approximately 17 wagons per day to meet injection rates. Surface facilities include storage, compression, heating, and safety systems enabling continuous injection. Operations fall under strict SEVESO and ICPE regulatory frameworks with robust HSE management.

A **preliminary risk assessment** identified key risks related to permitting, policy, CO_2 supply, and public acceptance. Technical risks such as leakage or seismicity are considered moderate to low and manageable.

A **comprehensive monitoring plan** covers well, storage, subsurface, and surface systems using seismic, fiber-optic, and geochemical tools. Monitoring extends through injection and up to 8 years post-injection to ensure long-term containment.

Overall, the study demonstrates **technical feasibility, regulatory compliance, and safe operation** of the CO_2 storage pilot.

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2. Ebro Basin (Spain)

The Ebro Basin CO_2 storage project proposes a full lifecycle assessment of an onshore storage system at ~1700 m depth. It includes exploration, a 3-year pilot injection phase, and a future commercial deployment stage. The study focuses specifically on the storage component, excluding capture and transport.

A preliminary vertical **injection well** has been designed to target the Buntsandstein formation. The design prioritizes operational safety, environmental protection, and reliable reservoir characterization. Historical offset wells (1958–1981) were analysed to identify drilling risks and uncertainties. Key drilling challenges include mud losses, clay swelling, borehole instability, and tight hole conditions. These findings informed a four-section well design with optimized casing and drilling fluids, including CO_2-resistant materials to ensure long-term integrity under corrosive conditions. Estimated drilling duration is approximately 116 days, with a total well cost is around €10.8 million, including injectivity testing and abandonment. The design remains conceptual and will require further engineering refinement. A structured **permitting roadmap** defines the regulatory pathway under Spanish law. The process starts with an investigation permit and progresses to a storage concession. Environmental Impact Assessment (EIA) and municipal permits are key requirements.

Operational logistics rely on a centralized warehouse system supporting drilling operations. This system manages inventory, quality control, transportation, and emergency response. Efficient logistics are critical due to limited local oil and gas infrastructure. A comprehensive logging program to support geological and reservoir evaluation; injectivity tests to assess reservoir performance and capacity, and long-term well maintenance plan to ensure integrity are also considered.

The **HSE framework** adopts a "Zero Harm" approach aligned with EU CCS Directive standards. It includes risk assessments, training, stakeholder engagement, and emergency planning. Key risks include leakage through legacy wells, induced seismicity, and regulatory delays.

Social acceptance and environmental sensitivity are critical factors in the Belchite area. A conceptual HAZID identifies environmental, technical, regulatory, social, and economic risks. These risks are considered manageable with proper mitigation and monitoring strategies.

A **risk-based MMV plan** ensures monitoring of containment, conformance, and performance. Technologies include VSP, DAS, InSAR, groundwater monitoring, and soil gas surveys. Monitoring baseline, injection, closure, and post-closure phases are included. An **Emergency response** is structured through an Incident Command System with defined escalation levels.

Overall, the project demonstrates **technical feasibility, regulatory compliance, and robust risk management**.

3. Lusitania Basin (Portugal)

The Lusitanian Basin project defines a pilot-scale offshore CO_2 storage system in shallow waters (~85 m) offshore Portugal. It is designed as a non-commercial demonstration within the PilotSTRATEGY framework. The concept uses ship-based CO_2 injection, avoiding permanent offshore infrastructure. Injection volumes are limited to less than 100 kt CO_2, ensuring proportionality to pilot objectives. Operations rely on existing infrastructure, particularly the Port of Figueira da Foz. The project integrates well design, transport, conditioning, monitoring, HSE, and permitting aspects.

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Well design is based **considering existing legacy wells**, especially Dourada-1, providing key insights into regional geology and operational risks. A single offshore injection well is planned to ~1400 m depth. The well includes conductor, surface, intermediate, and injection casing/liner. CO_2-resistant materials and cement ensure long-term integrity and containment. Drilling will use a jack-up rig with an estimated duration of 20–30 days. **Logging** (LWD and wireline)**, coring, and testing activities** may take an additional 10–15 days. A **water-based injectivity test** (DST) will confirm reservoir performance before injection in both cases by a dynamically positioned vessel connected to the wellhead via subsea systems. It is considered a CO_2 injection plan in discrete batches synchronized with the transport cycle.

The **transport chain** is modular: capture → liquefaction → rail transport → port transfer → ship injection. Each cycle transports about 650 t of CO_2, with total injection achieved in ~15 months. CO_2 is conditioned to ensure dense-phase injection (~51 bar, 14 °C at wellhead). Thermal and pressure control prevent phase changes and ensure flow stability.

The pilot operates under **Portuguese regulations** as a research activity with simplified permitting. Required approvals include drilling authorization, EIA, and maritime permits (TUPEM). HSE management follows offshore oil and gas industry standards and best practices. Key risks include weather conditions, well integrity, CO_2 leakage, and marine operations.

Risk assessment shows technical risks are low to moderate and well controlled. Main critical risks relate to permitting, funding, and stakeholder acceptance. A multi-barrier approach ensures risks are reduced to ALARP and "Not Significant" levels.

The **MMV plan** is risk-based and multi-layered across reservoir, well, seabed, and water column. Monitoring combines seismic surveys, DAS, geochemical sampling, and environmental observations for baseline, injection, and post-injection phases. Trigger thresholds (pressure, seismicity, integrity) enable adaptive operational control. Estimated MMV costs range from €3.2M to €4.6M, consistent with pilot scale.

Overall, the project demonstrates **feasible, safe, and regulation-compliant offshore CO_2 storage**.

4. Silesia Basin (Poland)

The Upper Silesia CCS project is designed as a phased **feasibility study** rather than a full commercial development. It targets a Jurassic saline aquifer with an estimated capacity of ~30 Mt CO_2 and favourable reservoir properties. The region hosts multiple nearby industrial emitters, supporting the development of a CCS hub.

The **pilot phase** plans to inject ~30 kt CO_2/year over three years using a single well and road transport. This phase aims to test injectivity, pressure behaviour, and monitoring rather than achieve profitability. The **commercial phase** would scale up to ~300 kt/year over 25 years, likely using pipelines.

System performance depends mainly on **pressure management** rather than storage capacity. A risk-based monitoring system integrates subsurface and surface measurement techniques.

Economic viability depends on scale, infrastructure, and CO_2 price incentives under the EU ETS.

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Overall feasibility relies on **technical validation, regulatory conditions, and stakeholder acceptance**.

5. Macedonian Basin (Greece)

The Mesohellenic Trough in the Macedonia Basin is defined as a **large-scale CO_2 storage system** controlled by capacity, pressure, and operational factors. Key formations (Pentalofos and Eptachori) provide very large storage capacity (~1.15–1.45 Gt CO_2), confirming regional significance. The basin is linked to nearby emission sources, particularly the Ptolemaida V power plant. The basin is best seen as a **regional CCS hub** rather than a single storage site.

Development follows a staged approach, starting with the most accessible parts of the system. System performance depends on maintaining sufficient CO_2 throughput and efficient infrastructure use. Injection is limited by **pressure constraints,** requiring multiple wells and distributed injection.

Economic viability improves when operating near full capacity with adequate carbon pricing. The system evolves progressively, expanding infrastructure and storage zones over time.

It has **strong potential to support large-scale and cross-border decarbonization in Southeast Europe.**

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3. Introduction

The PilotSTRATEGY project is investigating geological CO_2 storage sites in 5 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. Within the framework of Work Package 4, the consortium partners (IGME, REPSOL, BRGM, GEOSTOCK, CIEMAT, UEVORA, GALP, GIG, CERTH) have developed an optimized pilot project for CO_2 geological storage, ensuring technical robustness, economic feasibility, and compliance with the highest industry standards for health, safety, and environmental protection (HSE). The design and development process have integrated best practices and lessons learned from previous and ongoing European initiatives.

The optimized pilot scheme has comprised four main components:

- **Well Drilling and Completion Design (Injection and Monitoring Wells),** formulating alternative well design options, incorporating geological, geomechanical, and hazard information generated in WP2, together with modelling results from WP3; conducting iterative technical–economic evaluations to determine the most suitable well configuration, and preparing comprehensive technical and HSE documentation, including well construction plans, permitting requirements, operational procedures, logistics and maintenance plans, emergency response protocols, and well-containment strategies.
- **Capture, Transport, and Storage Facilities Outline**, identifying applicable CO_2 capture technologies for the selected emission source; assessing transport options; considering CO_2 stream quality and expected volumes, and developing the conceptual design of reception and injection facilities, including systems for pore-pressure management.
- **Multicriteria risk assessment,** aiming to demonstrate that the proposed CO_2 storage pilot can be implemented without significant risk to containment integrity, human health or the environment, in accordance with Directive 2009/31/EC. Corrective and preventive measures have been defined applied to the final development proposal, including the MMV Plan.
- **Monitoring Strategy and Corrective Measures,** developing an MMV Plan to cover the pre-injection, operational, and post-injection phases with the goal of ensure long-term storage integrity; warning of operational anomalies; track the spatial and temporal evolution of the CO_2 plume, and verify the quantity, composition, and behaviour of the injected CO_2.

A preliminary evaluation of the well and injection facilities design has been shared in the deliverable **D4.4** *Injector well and injection facilities design: methodology, definition and recommendation,* with a general overview of the full chain CCS possibilities in the deliverable **D4.5***: From capture to the injection facilities definition: capture, transport, and CO2 stream quality.* Studied options have been techno-economically assessed and selected the optimum option, as it is presented on the deliverable **D4.9** *Economic evaluation of alternatives and priorization of results,* and **D4.11** *Description and results of the probabilistic assessment and sensitivity analysis of the development concept.* Finally, the environmental legal requirements and permitting process are collected on the **D4.7** *Compiling of Environmental Impact assessment legal frame and permit requirements for CO2 geological storage.*

In this report **D4.6** *Permit Dossier: Operation, logistics and well maintenance plans description, Well permits road map, MMV plan and HSE, emergency response and well containment plans,* we aim to provide a comprehensive overview of the legal and regulatory requirements associated with the permitting process for CO_2 storage pilot operations with a level of detail appropriate to both the current maturity of the project and the specific national regulatory frameworks involved.

To support future implementation and facilitate the preparation of subsequent project phases, the deliverable presents three detailed case studies corresponding to the main areas under consideration—the Paris Basin, the Ebro Basin, and the Lusitanian Basin—together with a general regulatory overview for Poland and Greece. These examples are intended to serve as practical guidance for future users and stakeholders, illustrating the procedural steps, documentation needs, and regulatory interactions required in each jurisdiction.

This deliverable also provides a foundational reference for the preparation of D4.12 – *Pre-FEED and Final Proposal for a Concept Development by Regions*, ensuring that the permitting, operational, monitoring, and HSE considerations are fully integrated into the final investment proposal.

4. Paris Basin (France)

4.1 Introduction

The French case (Canteli *et al.*, 2025b) is based on a pilot-scale injection for a next-to-the-area emitter, which provides CO_2 stream at the commercial rate (300 kt/y), and with a limit of total injection of 100 kt of CO_2, as discussed and presented to local stakeholders in WP6. The CO_2 stream is almost pure CO_2 produced from SMR (steam methane reforming) operations at the plant. The plant is operating a waste-water disposal well (vertical open-hole).

The case was revised for Milestone MS43 (October 2025) to account for changes in the emission of the plant which led to an additional scenario which considers non-local CO_2 source which will be transported to the plant site by train. The external source is not identified within the project.

Therefore, the project considers four scenarios as illustrated in Figure 1:

- different wellhead locations: onsite - offsite
- different CO_2 sources: local – external

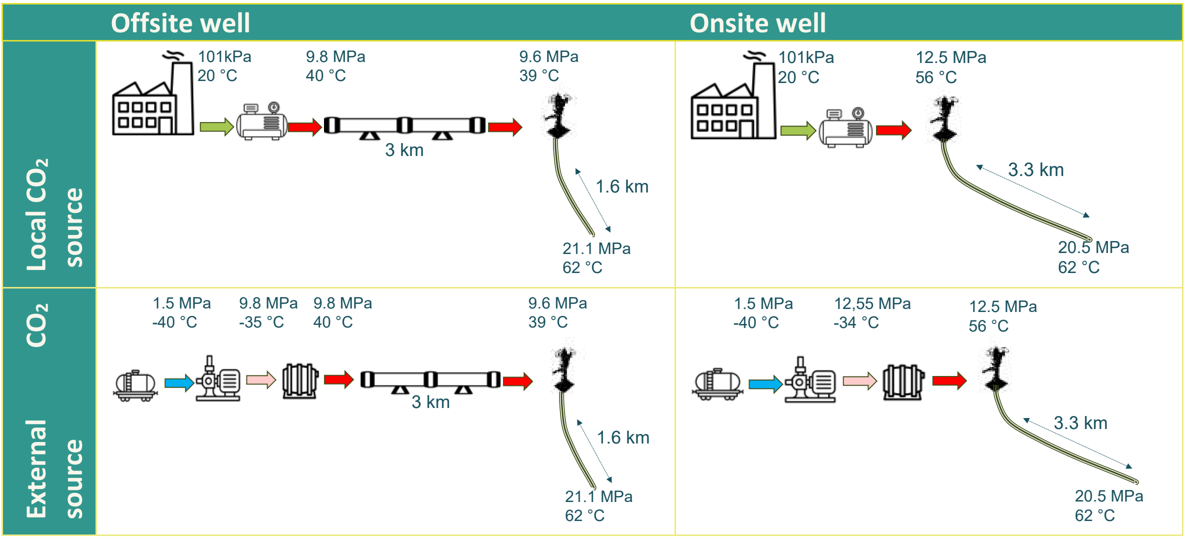

Figure 1 Development scenarios considered for a CO2 injection pilot project in Paris Basin

The technical specifications of the various equipment (pipeline, well, compression…) are detailed in D4.5 (Lachén *et al.*, 2025). The different scenarios were elaborated such that the CO_2 is under the same conditions at the gate fence of the plant thus maintaining the downstream conditions and equipment.

4.2 Technical specifications of the CO_2 injection pilot

The well designs were elaborated in D4.5 (Lachén *et al.,* 2025) for the two well trajectories and recalled in Figure 3 and Figure 4. There is no additional change except for detailed description of the logging program and brine injectivity tests (see section 4.2.2)

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4.2.1 Planning of well operations

Under the French regulation the administrative review shall take place during about 2 years which involved reviews at different levels of the administration, local and national (Figure 5) as detailed in D4.7 (Chávez *et al.,* 2025).

The planning for construction of the equipment (well and surface facilities) is shown in Figure 5 and should be completed within three years after the permit is granted pending upon the long lead item delivery. The long lead items concern the procurement of the casing and well head along with the availability of the drilling rig but also the compressor. These procurement contracts should be anticipated as much as possible to shorten the lead time before construction. It was assumed that the procurement should last about one year considering the current market conditions in France for such items (Figure 5). The civil works indicated in Figure 5 correspond to the setup of the well pad and the conditioning platform (compression or pumping station) within the plant premises together with a detailed soil survey along the proposed pipeline route considering the safety regulation with existing gas pipeline infrastructure.

Prior to any planned on-site work, the work permits shall be obtained from the administration to ensure safe operations as highlighted in Figure 2.

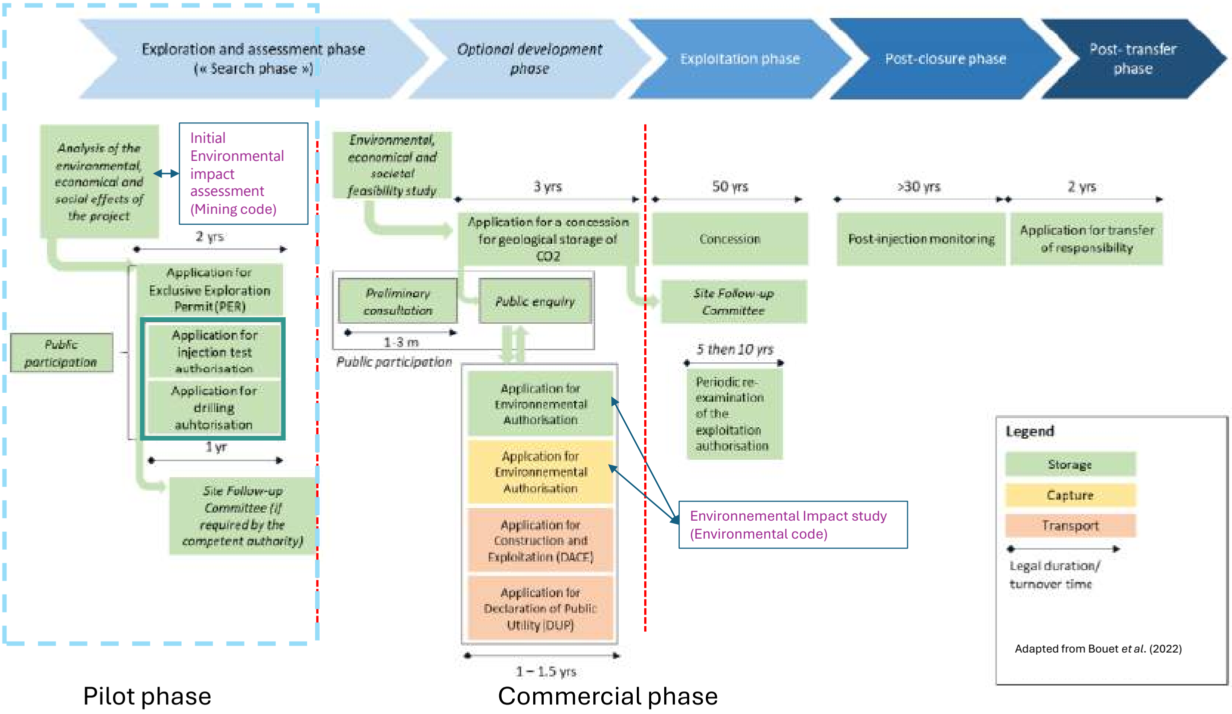

Figure 2 French permitting process for CO_2 geological storage (Bouet et al, 2022)

The planned work should start with the well drilling and completion before the brine injectivity test to confirm the injectivity (see section 4.2.2.2). Then, the surface installation shall be built to enable CO_2 delivery to the wellhead depending on the scenario that is implemented (Figure 1).

The injection operations are planned to last 3 months. Therefore, no specific maintenance is planned for such a short period of operation.

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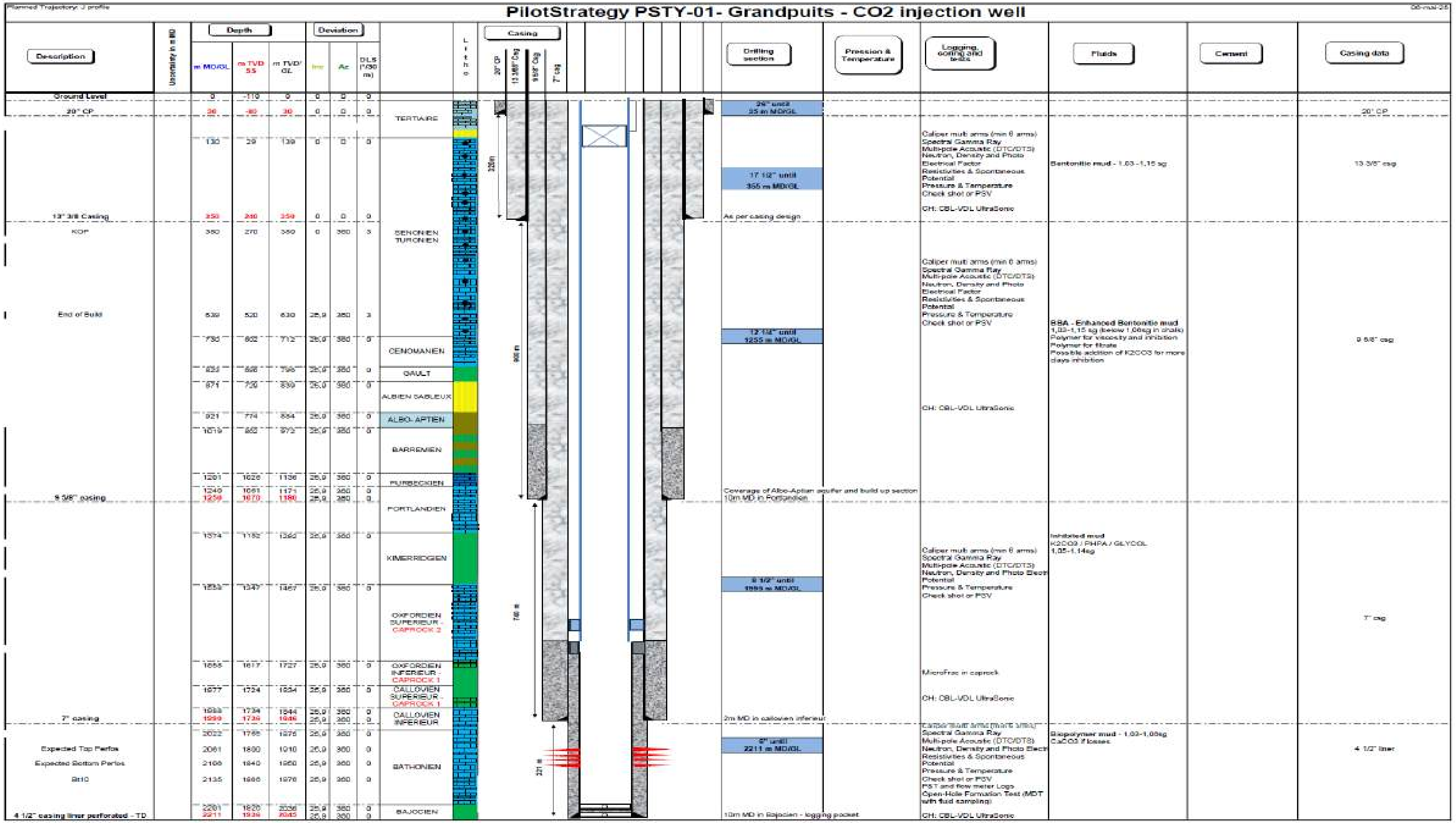

Figure 3 PSTY 01 Standard J profile well architecture diagram

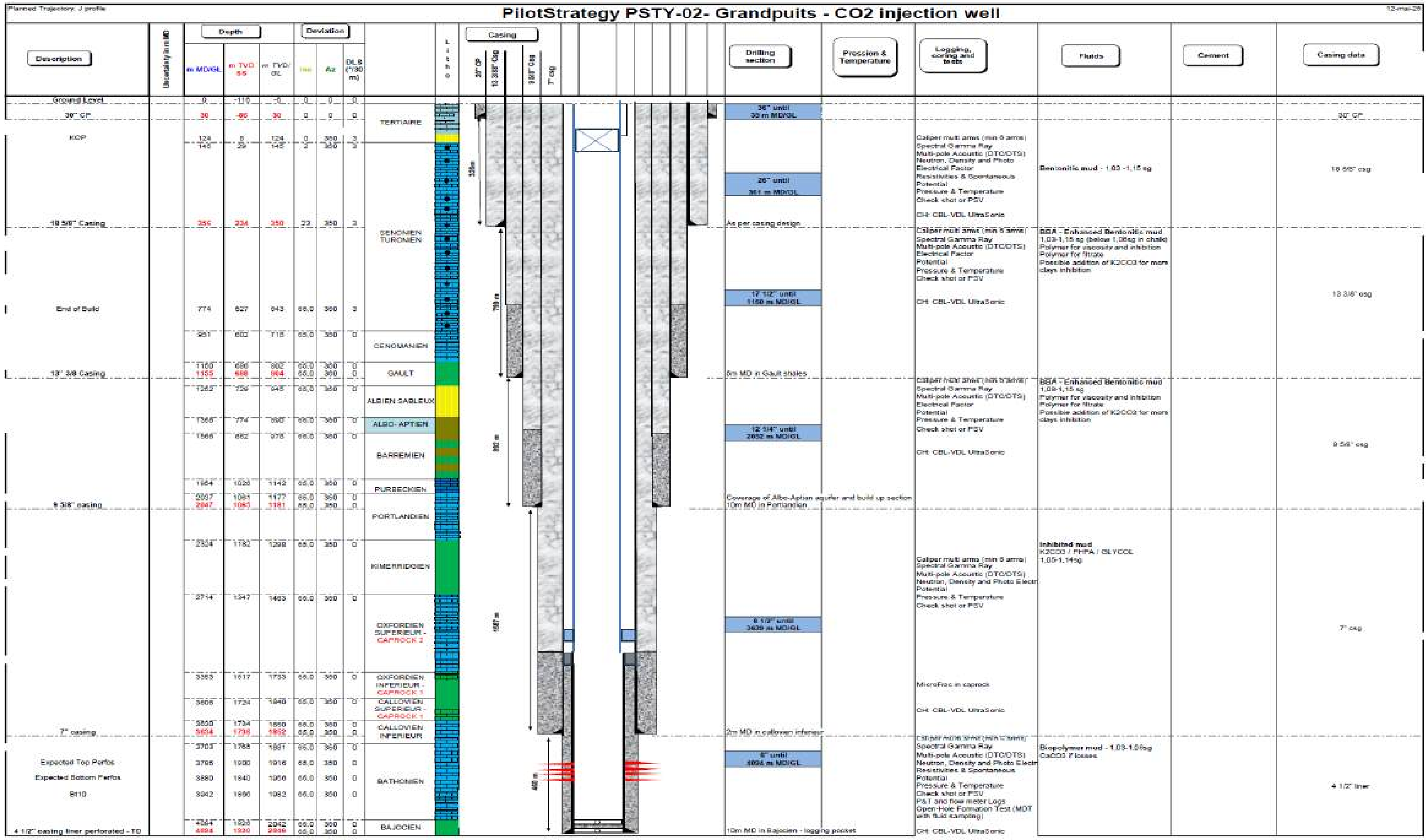

Figure 4 PSTY 02 Deviated long J profile well architecture diagram

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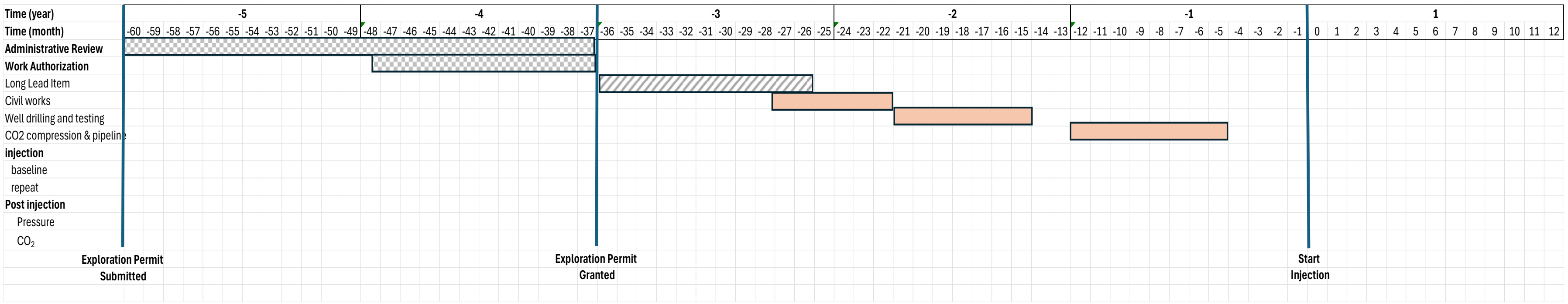

Figure 5 Foreseen planning for administrative review and construction of infrastructures

			offsite	onsite	Pressure, Temperature, Density	Gamma Ray	Caliper multi-arms	Sonic Compressional (DTC)	CBL-VDL	Spectral Gamma Ray	Neutron Porosity	Density + PEF	Resistivities + SP	USIT	MicroFrac	MDT + Fluid Sample	Borehole Imager	Nuclear Magnetic Resonance	Coring
overburden	TERTIAIRE	Oligocene	20"	36"															
	CRETACE	Eocene	17,5"	26"															
		Senonien Turonien																	
		Cenomanien	12,25"	17,5"															
		Albien argileux (Argiles du Gault)																	
		Albien sableux - Sables		12,25"															
		Albo aptien																	
		Barremien																	
	URASSIQUE	Neocomien																	
		Purbeckien																	
		Portlandien																	
		Kimmeridgien	8,5"	8,5"															
		Oxfordien supérieur - Lusitanien																	
caprock	DOGGER	Oxfordien inférieur																	
		Callovien supérieur CA28																	
storage		Callovien inférieur - Dalle nacrée - Comblanchien = CA26																	
		Bathonien - Oolithe Blanche = SB_Comb	6"	6"															
		Bathonien - Bt10																	
	LIAS	Bajocien = BJ1																	
		Aalenien																	
		Toarcien																	

Figure 6: Planned logging acquisition.

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4.2.2 Well integrity and injectivity

The well integrity must be validated prior to any injection operation. Such validation is a multistep operation which includes measurements during the drilling and before completing the well and hydraulic test after well completion. The corresponding cost of the foreseen acquisition program are estimated.

4.2.2.1 Logging acquisition program

The initial logging campaign performed during the well drilling operations is considered as included in the CAPEX. The repeat logging campaign that is foreseen at or after the end of the injection is considered as OPEX.

The logging program D4.5 (Lachén *et al*., 2025) was tuned to focus primarily on the caprock and storage formations (Figure 6). The required logging in the overburden is minimized given the extensive drilling experience in the Paris Basin.

Electrical logging encompasses all standard acquisitions essential for petrophysical interpretations and well quality control (e.g. open hole evaluations and cement quality verification). Other e-line operations refer to specialized acquisitions that require dedicated tools and/or specialized crews (e.g. pressure tests, micro fracturing tests and fluid sampling).

The cost estimation for well logging and other e-line operations has been carried out in alignment with the exploration program defined in the forecast well designs (D4.5 Lachén *et al*., 2025).

Given that the geological column and rock units of the Paris Basin are already well characterized, the initial program was revised to optimize overall costs, particularly for the upper drilling phases (above the seal - overburden). Within this framework, only data acquisitions considered essential for well construction and for enhancing seismic interpretation were designated as critical to the project. Accordingly, Caliper, Gamma Ray, Sonic (DTC) and CBL-VDL logs were retained as critical, while all other initially planned measurements were reclassified as optional.

Estimates were prepared on a per-well basis considering all drilling phases and the two acquisition categories: critical (“must have”) and optional (“nice to have”). Unit prices for each acquisition were derived from quotations provided by drilling contractors for recent European exploration drilling campaigns. The adopted cost ranges are representative of the European market and consistent with the project’s geographical context. To develop a cost range based on available price lists, maximum (MAX) and minimum (MIN) unit prices were established for each acquisition category.

For conventional logging operations which require only standard tools and not specialized equipment, a single mobilization/demobilization was allocated per drilling section, covering all conventional logging activities. For specialized acquisitions (e.g. pressure tests, micro fracturing tests and fluid sampling), an additional mobilization/demobilization charge was systematically included for each intervention due to the need for dedicated crews and specialized equipment not typically provided by conventional logging service companies.

The cost model for each acquisition comprises two components:

- Depth charge: the cost associated with deploying and retrieving the tool, calculated over the measured depth from the surface to the deepest point of investigation.

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- Acquisition/measured charge: the cost associated with the measurement itself, typically based on either the logged interval (top to base) or the number of discrete test points planned.

For micro fracturing tests in the seal intervals, ten measurements were assumed: three points (top, middle, and base) for each of the three sealing rock units, plus one additional point determined from drilling observations. For pressure measurements and fluid sampling in the seal section, ten test points were considered to characterize potentially porous and permeable intervals encountered during drilling.

Within the reservoir unit, the objective of conducting DST or MDT operations as part of the CO_2 injection project is to obtain representative in-situ fluid samples and perform an injectivity assessment. Based on the expected reservoir thickness, ten sampling points were assumed.

The estimated budget range for PSTY01 well (Table 1) is between 0.848 and 1.623 million euros for acquisitions designated as critical and between 0.539 and 0.920 million euros for acquisitions categorized as optional.

WELL PSTY 01						
Drilling section	Size (OD)	OH	COST ESTIMATION (k€)			
			MUST HAVE		NICE TO	
			MIN	MAX	MIN	MAX
Section 0	20”	26”	-	-	-	-
Section 1	13-3/8”	17-1/2”	38	49	17 k€	64 k€
Section 2	9-5/8”	12-1/4”	72	118	65 k€	218 k€
Section 3	7”	8-1/2”	319	643	325 k€	425 k€
Section 4	4-1/2”	6”	419	813 000€	132 k€	213 k€
		TOTAL	**848**	**1 623**	**539**	**920**

Table 1 logging program for PSTY01 well (offsite)

The estimated budget range for PSTY02 well (Table 2) is between 1.376 and 2.843 million euros for acquisitions designated as critical and between 0.939 and 1.710 million euros for acquisitions categorized as optional.

WELL PSTY 02						
Drilling section	Size (OD)	OH	COST ESTIMATION (k€)			
			MUST HAVE		NICE TO	
			MIN	MAX	MIN	MAX
Section 0	30''	36''	-	-	-	-
Section 1	18-5/8''	26''	37	50	19	66
Section 2	13-3/8''	17-1/2''	68	112	60	201
Section 3	9-5/8''	12-1/4''	105	189	104	321
Section 4	7''	8-1/2''	497	1 084	514	718
Section 5	4-1/2''	6''	669	1 408	242	404
		TOTAL	**1 376**	**2 843**	**939**	**1 710**

Table 2 : logging program for PSTY02 well (onsite)

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4.2.2.2 Injectivity test

This section summarizes the definition, hypothesis and main results of the simulation study conducted to support the preliminary design of the injectivity test for the CO_2 injection well. Prior to CO_2 injection, the initial injectivity tests will be carried out with brine, compatible with the storage brine to avoid scaling issues. Besides injectivity, the pressure buildup and fall-off will be carefully monitored for an extended period to assess the possible flow barriers in the storage formation (D4.5 Lachén *et al.*, 2025).

The results presented aim at giving a preliminary estimation of the well tests sequence with associated costs and conditions including:

- Brine rates to be injected.
- Approximative injection period duration.
- Approximative stand-by/observation time.

4.2.2.2.1 Well test design methodology

The well test design presented in this document was completed using Saphir™ software. The principle of test design is to run a simulation of the pressure response from an input test sequence and a set of assumed parameters, and to store this simulation as if it was a set of pressure data. The input test sequence is investigated and optimized during the simulation study and the set of assumed parameters are the reservoir and well characteristics expected for CO_2 storage reservoir and the CO_2 injection well design

- The reservoir properties and the initial conditions from the reservoir modelling of the area of interest (D3.3, Chassagne *et al.*, 2024)
- The potential characteristics of the proposed injection well (D4.5, Lachén *et al.*, 2025).

4.2.2.2.2 Input data and hypothesis

The interval of interest is the Oolithe Blanche limestone, the target storage formation, expected to be encountered at a formation top depth of 1734 m. The expected reservoir properties in terms of porosity and permeability are those corresponding to the P10_PSC, P50_BC and P90_OPT static models (Bouquet *et al.*, 2024) summarized in Table 3:

Case	Permeability (mD)	Porosity
P10	52	0.147
P50	70	0.158
P90	149	0.196

Table 3 : Reservoir permeability and porosity from static modelling

Additionally, a few sensitivity cases were simulated to explore the impact of better reservoir properties.

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The fluid initially present in the reservoir is expected to be salted water (hydrostatic initial state assumed) at an Initial pressure of 190 bar at 1850 m TVDSS (D3.3, Chassagne *et al*., 2024). The CO_2 injection well is assumed to be vertical with a radius of 0.069 m (D4.5, Lachén *et al*., 2025).

4.2.2.3 Simulation cases

The cases investigated during the simulation study are the following (Table 4):

Simulation case	Permeability (mD)	Porosity	Test flowrate (m^3/d)
P10	52	0.147	50
P50	70	0.158	65
P90	149	0.196	140
P50 x 5	350	0.2	300
P50 x 10	700	0.2	600

Table 4 : List of simulation cases

4.2.2.3.1 Design of observation period duration

After the brine has been injected into the reservoir it is necessary to record the pressure response for a few days to obtain enough data to analyze the characteristics of the near well zone and the reservoir formation investigated. According to the simulation results, a few days of pressure observation (1 to 5 - without brine injection) will be sufficient to confirm the characteristics of the near wellbore zone and the reservoir formation properties around the well. Although no faults were identified in the area of interest, an investigation of the duration of the observation periods allows to identify potential barriers to flow in the expected storage zone has been investigated.

A sensitivity study was completed to account for hypothetical cases including flow barriers that could be encountered at a distance between 1 to 5 km. For every combination of potential reservoir properties (Table 4), the observation time that would be needed to identify a flow barrier at 1, 2, 3, 4 and 5 kilometers is investigated.

Table 5 summarizes the results obtained for all simulated cases showing that the flow barriers could be observed after a stand-by period ranging from 10 to 45 days depending on the actual reservoir properties (min and max cases).

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Simulation case	Permeability (mD)	Porosity	Min observation time (for barrier at 1 km) (days)	Max observation time (for barrier at 5 km) (days)
P10	52	0.147	5	45
P50	70	0.158	3	40
P90	149	0.196	2	30
P50 x 5	350	0.2	1	20
P50 x 10	700	0.2	1	10

Table 5 : Simulation results summary: Observation period duration

The detail of the results obtained for each sensitivity case: distance of 1,2,3,4,5 kilometers to the flow barrier is presented in Figure 7

4.2.2.3.2 Main results

The main results of the simulation study are as follows:

- **Water injection flowrate:** water rates ranging from 50 to 600 m^3/day should allow to create a pressure response
- **Water injection period duration**: an injection period of 5 days should allow for a pressure response to be recorded in the injection well.
- **Observation period duration**: although no faults were identified in the area of interest, hypothetical cases including barriers to flow that could be encountered at 1 to 5 km were simulated. The impact of the faults could be observed in the well-test interpretations for data acquired during a stand-by period of 5 to 45 days.
- **Total well test duration:** the approximative total test duration for the simulated cases ranged between 10 and 45 days.

4.2.2.3.3 Cost estimates

The expected duration of the test will be included in the cost estimates of the injectivity test of the well as CAPEX based upon the mobilization/demobilization and daily cost of the test rig. The cost for the injectivity tests ranges between 192 and 738 k€.

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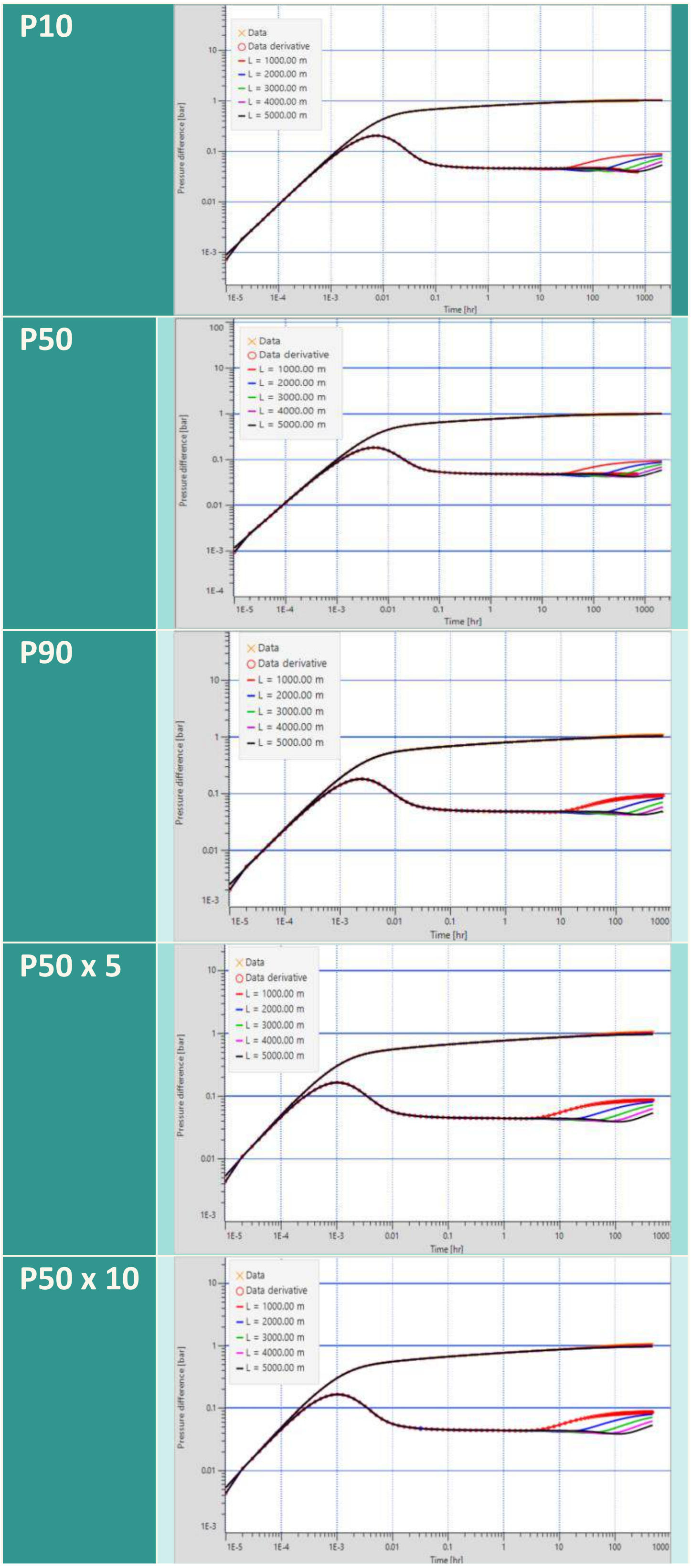

Figure 7: Results of the interpretation of well test case for hypothetical cases of flow barriers at 1,2,3,4,5 kilometres from the injection well.

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4.2.3 CO_2 conditioning plant

4.2.3.1 Local CO_2

In this initial scenario, the CO_2 will be produced during the plant operations. The designs were elaborated in D4.5 (Lachén *et al.,* 2025) for the two well trajectories and recalled in Figure 8 and Figure 9.

4.2.3.2 External CO_2

In this alternative scenario, the CO_2 will be transported by railway wagons. The unloading station of the wagons will be located at the local rail connection at the plant.

The well designs were elaborated in D4.5 (Lachén *et al.,* 2025) for the two well trajectories are shown in Figure 3 for the slightly deviated J-shape well and Figure 4 for the long-deviated deviate J-shape well.

For the Paris Basin case, two scenarios are considered:

1. main scenario: a slightly deviated J-shape well with a pipeline transport of about 3 km
2. alternate scenario: a long-deviated J-shape well without pipeline transport

Based upon the well design in D4.5 (Lachén *et al.,* 2025), the wellhead conditions are summarized in Table 6:

scenario	Pwellhead (kPa)	Twellhead (°C)
main	96500	39
alternate	12500	56

Table 6: Summary of the wellhead conditions for the scenarios considered for the French case

4.2.3.2.1 Main scenario

This scenario considers a J-shape well with pipeline transport. The unloading station of CO_2 is located about 3 km from the wellhead. The process flow diagram is shown in Figure 10.

4.2.3.2.1.1 General description

The CO_2 will be transported by wagons. Each wagon will contain 50 t of liquid CO_2 at -40°C and 15 barg. Therefore, to meet the required injection rate (300ktpa), 17 wagons should be unloaded per day.

The wagon will be connected to an unloading skid which is composed of:

- one unloading arm for liquid CO_2, with a diameter of 3”;
- one arm to inject vaporized CO_2 in the wagon;
- a small buffer tank;
- a compressor;
- the required configuration valves;
- pressure safety valves;
- a control panel.

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For unloading operations, the suction of the compressor will be directed towards the storage. The discharge will be oriented to the wagon to be unloaded. Liquid discharge line should be connected to both the “load to” and “unload” vessel. While the compressor is running, vapor will be removed from the storage, compressed and pushed to the wagon. A pressure differential will be made, and the liquid will begin to flow from the wagon to the storage. Once flow of liquid has been completed, the compressor will be stopped.

Then the liquid CO_2 will pass in a buffer tank. This tank will store CO_2 during the unloading operation and inject CO_2 into the reservoir during the night, to inject continuously CO_2 into the well. The tank will be equipped with a vaporizer in order that when it is withdrawn, its pressure will stay constant.

Then the CO_2 will be pumped and heated to reach 40°C and to be injected into the well at the required temperature. The pipeline between the installations and the wellhead has an estimated diameter of 6’’. This diameter is chosen by applying velocity design criteria on the detail of the routing of the pipeline. Safety valves will be installed in different areas to isolate the installation in case of emergency.

4.2.3.2.1.2 Description of the main equipment

As defined in Figure 10, the equipment is designed as:

- Storage buffer tank (V1) will have a working volume of 240 m^3, an operating pressure of 15 barg and an operating temperature of -40°C
- Pump P-1 will have a suction pressure of 14.5 barg, a discharge pressure of 97.8 barg, a flowrate of about 34.2 t/h and an estimated power of 95 kW
- Electrical heater (E1) will have an upstream pressure of 97.8 barg, an upstream temperature of -35°Cand a downstream temperature of +40°C for a flowrate of about 34.2 t/h and an estimated thermal power of 1980 kW

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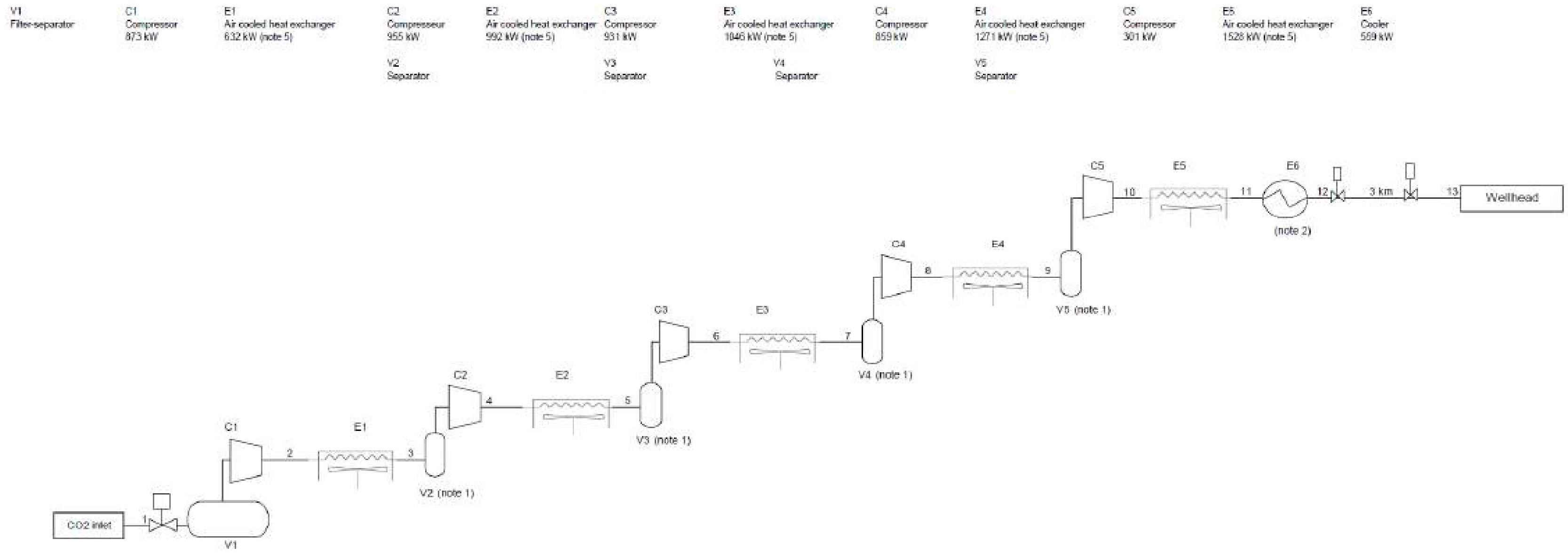

STREAM		1	2	3	4	5	6	7	8	9	10	11 (Note 3)	12 (Note 3)	13 (Note 3)	11 (Note 4)	12 (Note 4)	13 (Note 4)
MASS FLOW	kg/h	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247
ACTUAL VOLUME FLOW	m3/h	18 790	8 436	8 222	3 668	2 876	1 291	926	427	251	182	101	68	68	68	68	68
TEMPERATURE	°C	20	122	50	160	50	160	50	160	50	98	50	40	39	40	40	39
PRESSURE	kPa	101	304	254	762	712	2 125	2 075	6 073	6 023	9 940	9 890	9 840	9 655	9 840	9 840	9 655
Mass DENSITY	kg/m3	1,8	4,1	4,2	9,3	11,9	26,5	37,0	80,2	136,5	187,9	339,2	506,8	503,1	506,8	506,8	503,1
VISCOSITY	cP	1,44E-02	2,02E-02	1,61E-02	2,24E-02	1,63E-02	2,28E-02	1,68E-02	2,41E-02	1,94E-02	2,39E-02	2,81E-02	3,90E-02	3,86E-02	3,90E-02	3,90E-02	3,86E-02
MOLECULAR WEIGHT	g/mol	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44	44
Z FACTOR		0,99	0,99	0,99	0,99	0,97	0,97	0,91	0,92	0,72	0,75	0,47	0,33	0,32	0,33	0,33	0,32
Cp/Cv		1,29	1,26	1,28	1,26	1,31	1,29	1,40	1,39	1,98	1,88	4,99	7,98	8,46	7,98	7,98	8,46
CO2 MOLE FRACTION		0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99
H2 MOLE FRACTION		0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01

Notes:
1- Separator requirement to be confirmed by compressor vendor.
2- Cooler required when ambiant temperature higher than 30°C.
3- Stream data for ambiant temperature higher than 30°C (40°C).
4- Stream data for ambiant temperature of 30°C.
5- Thermal power

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Figure 8 Process Flow Diagram for the main scenario with local CO_2

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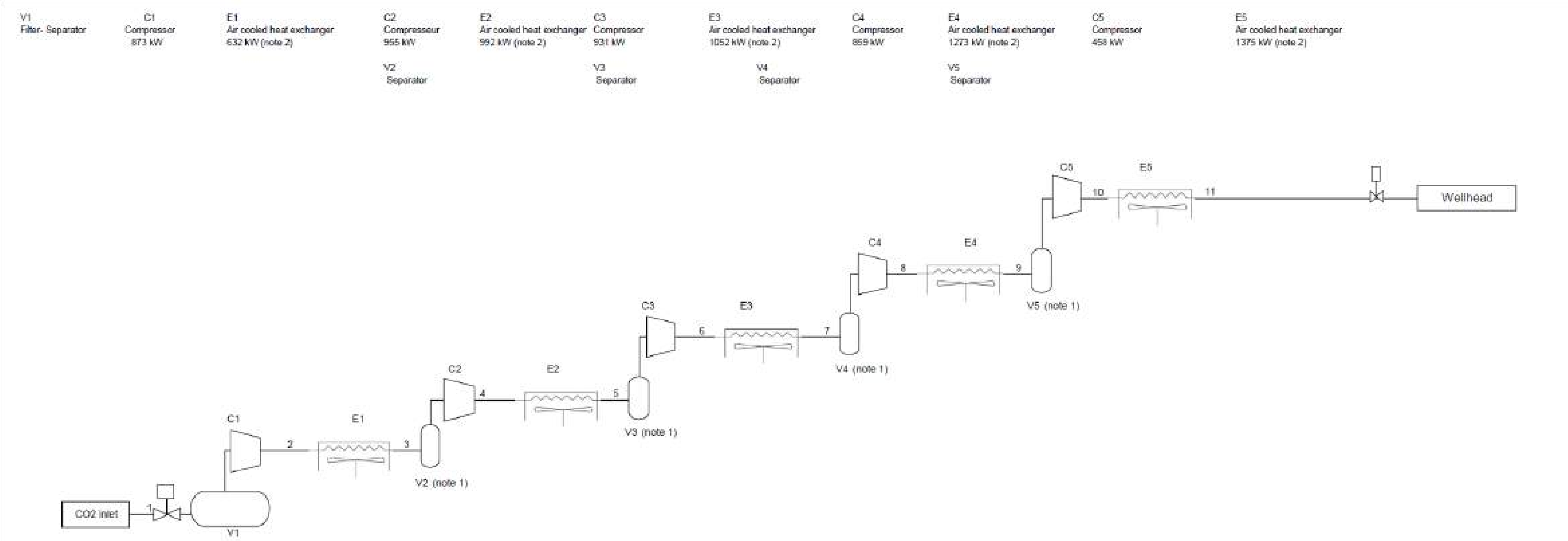

STREAM		1	2	3	4	5	6	7	8	9	10	11
MASS FLOW	kg/h	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247
ACTUAL VOLUME FLOW	m3/h	18 790	8 436	8 222	3 668	2 876	1 291	926	427	251	158	75
TEMPERATURE	°C	20	122	50	160	50	160	50	160	50	122	56
PRESSURE	kPa	101	304	254	762	712	2 125	2 075	6 073	6 023	12 550	12 500
Mass DENSITY	kg/m3	1,8	4,1	4,2	9,3	11,9	26,5	37,0	80,2	136,5	216,7	458,9
VISCOSITY	cP	1,44E-02	2,02E-02	1,61E-02	2,24E-02	1,63E-02	2,28E-02	1,68E-02	2,41E-02	1,94E-02	2,64E-02	3,64E-02
MOLECULAR WEIGHT	g/mol	44	44	44	44	44	44	44	44	44	44	44
Z FACTOR		0,99	0,99	0,99	0,99	0,97	0,97	0,91	0,92	0,72	0,77	0,43
Cp/Cv		1,29	1,26	1,26	1,26	1,31	1,29	1,40	1,39	1,98	1,83	4,63
CO2 MOLE FRACTION		0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99	0,99
H2 MOLE FRACTION		0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01

Notes:
1- Separator requirement to be confirmed by compressor vendor,
2- Thermal power

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Figure 9 Process Flow Diagram for the alternate scenario with local CO_2

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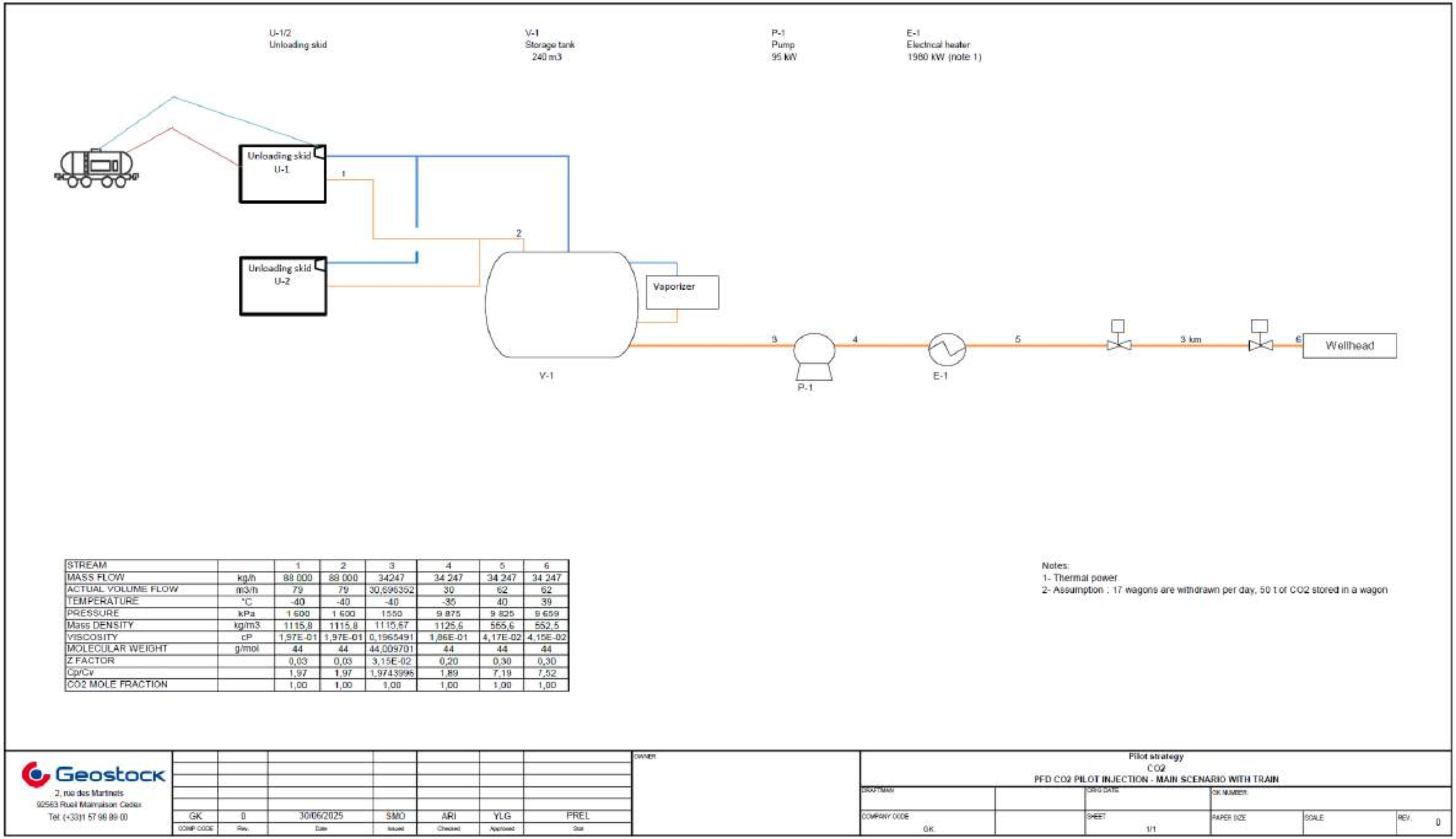

STREAM		1	2	3	4	5	6
MASS FLOW	kg/h	88 000	88 000	34247	34 247	34 247	34 247
ACTUAL VOLUME FLOW	m3/h	79	79	30,696352	30	62	62
TEMPERATURE	°C	-40	-40	-40	-35	40	39
PRESSURE	kPa	1 600	1 600	1550	9 875	9 825	9 659
Mass DENSITY	kg/m3	1115,8	1115,8	1115,67	1125,6	565,6	552,5
VISCOSITY	cP	1,97E-01	1,97E-01	0,1965491	1,86E-01	4,17E-02	4,15E-02
MOLECULAR WEIGHT	g/mol	44	44	44,009701	44	44	44
Z FACTOR		0,03	0,03	3,15E-02	0,20	0,30	0,30
Cp/Cv		1,97	1,97	1,9743996	1,89	7,19	7,52
CO2 MOLE FRACTION		1,00	1,00	1,00	1,00	1,00	1,00

Figure 10 Process Flow Diagram for the main scenario with external CO_2

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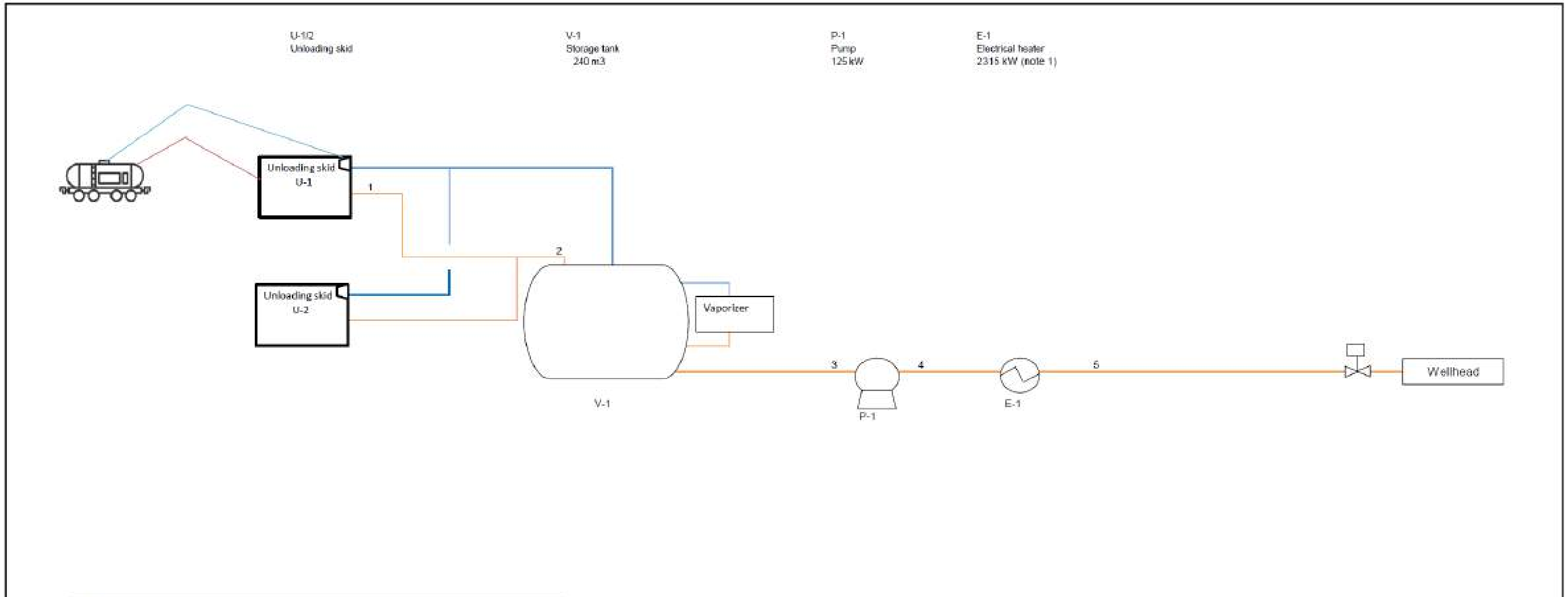

STREAM		1	2	3	4	5
MASS FLOW	kg/h	88 000	176 000	34247	34 247	34 247
ACTUAL VOLUME FLOW	m3/h	79	158	30,696352	30	71
TEMPERATURE	°C	-40	-40	-40	-34	56
PRESSURE	kPa	1 600	1 550	1550	12 550	12 500
Mass DENSITY	kg/m3	1115,8	1115,7	1115,67	1128,7	484,6
VISCOSITY	cP	1,97E-01	1,97E-01	0,1965491	1,83E-01	3,74E-02
MOLECULAR WEIGHT	g/mol	44	44	44,009701	44	44
Z FACTOR		0,03	0,03	3,15E-02	0,25	0,41
Cp/Cv		1,97	1,97	1,9743996	1,87	4,79
CO2 MOLE FRACTION		1,00	1,00	1,00	1,00	1,00

Notes:
1- Thermal power
2- Assumption : 17 wagons are withdrawn per day, 50 t of CO2 stored in a wagon

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Figure 11 Process Flow Diagram for the alternate scenario with external CO_2

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4.2.3.2.2 Alternate scenario

This scenario considers a long-deviated J-shape well and no pipeline transport as the wellhead is located within the wagon unloading station premises. The process flow diagram of this scenario is shown in Figure 11.

4.2.3.2.2.1 General description

The CO_2 will be transported by wagons. Each wagon will contain 50 t of liquid CO_2 at -40°C and 15 barg. Therefore, to meet the required injection rate (300ktpa), 17 wagons should be unloaded per day.

The wagon will be connected to an unloading skid which is composed of:

- one unloading arm for liquid CO_2, with a diameter of 3";
- one arm to inject vaporized CO_2 in the wagon;
- a small buffer tank;
- a compressor;
- the required configuration valves;
- pressure safety valves;
- a control panel.

For unloading operations, the suction of the compressor will be directed towards the storage. The discharge will be oriented to the wagon to be unloaded. Liquid discharge line should be connected to both the "load to" and "unload" vessel. While the compressor is running vapor will be removed from the storage, compressed and pushed to the wagon. A pressure differential will be created, and the liquid will begin to flow from the wagon to the storage. Once flow of liquid has been completed, the compressor will be stopped.

Then the liquid CO_2 will pass in a buffer tank. This tank allows to store CO_2 during the unloading operation and to inject CO_2 in the reservoir during the night, to inject continuously CO_2 in the well. The tank will be equipped with a vaporizer in order that when it is withdrawn, its pressure will stay constant.

Then the CO_2 will be pumped and heated to reach 56°C and to be injected into the well at the required temperature. The pipeline between the installations and the wellhead has an estimated diameter of 6''. This diameter is chosen by applying velocity design criteria on the detail of the routing of the pipeline. Safety valves will be installed in different areas to isolate the installation in case of emergency.

4.2.3.2.2.2 Description of the main equipment

As defined in Figure 11, the equipment is designed as:

- Storage buffer tank (V1) will have a working volume of 240 m^3, an operating pressure of 15 barg and an operating temperature of -40°C
- Pump P-1 will have a suction pressure of 14.5 barg, a discharge pressure of 124.5 barg, a flowrate of about 34.2 t/h and an estimated power of 125 kW

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- Electrical heater (E1) will have an upstream pressure of 124.5 barg, an upstream temperature of -34°C and a downstream temperature of +56°C for a flowrate of about 34.2 t/h and an estimated thermal power of 2315 kW

4.2.3.2.3 Other equipment

An emergency shut down (ESD) system is required. This system ensures that the different areas of the installation are sealed off in case of emergency.

The final design should consider implementing advanced leak detection technologies, such as infrared cameras and gas sensors, which can help identify and address CO_2 leaks promptly.

The site will be equipped too with:

- Open/closed drain system
- DCS & ESD system,
- TSV for portions of pipe that could be isolated
- Utilities for compressors (oil, cooling water…)
- Gas detection, fire detection, firefighting facilities,
- Vent stack for depressurization,
- Power supply,
- Building and control room.

For the main scenario, pig traps should be installed on both sides of the 3 km long pipeline.

4.3 Heath Safety Environment:

4.3.1 Organization Heath Safety Environment

As part of the CO_2 injection pilot in the Paris Basin, operations will be integrated into the existing HSE management system of the plant, which is already classified as a SEVESO high-threshold site. In the scenario where the facilities are located 3 km from the plant, the surface installations will also be classified as ICPE. The tests will be authorized by a prefectural decree and must comply with risk prevention requirements.

This framework covers major accident prevention, occupational health, and environmental protection, in compliance with ICPE and SEVESO requirements. The system relies on:

- A clear HSE policy addressing industrial safety, occupational health, and environmental protection, including a mandatory Major Accident Prevention Policy for SEVESO sites.
- A dedicated organization with defined roles and responsibilities (HSE manager, well manager, surface facilities manager).
- Operational procedures for critical phases (drilling, injectivity tests, injection, maintenance).
- Personnel training on specific risks associated with the facilities and ATEX rules for compression zones.

- An update of the plant's Internal Emergency Plan to incorporate risks related to the pilot project, or alternatively, an emergency management plan will need to be implemented to organize resources and emergency response around the surface installations.

4.3.2 Risk reduction

Risk reduction at source follows the ALARP principle and is based on technical specifications described in Section 4.2 and D4.5 (Lachén *et al*., 2025):

- **Well design (standard J and long-deviated J profiles):** CO_2-compatible materials, integrity checks (caliper, CBL/VDL, USIT), safety devices (SSSV, pressure/temperature gauges).
- **Injectivity test with brine prior to CO_2 injection (section 4.2.2.2):** sequences, durations, and pressure response monitoring to confirm absence of barriers and calibrate operating thresholds.
- **Surface facilities and compression:** ATEX zoning, redundant instrumentation (pressure/temperature/flow), valves and relief devices, hierarchical emergency shutdown, mechanical ventilation of enclosed areas.
- **CO_2 pipeline (depending on scenario):** mechanical protection, cathodic protection, sectioning valves, continuous fiber-optic monitoring (DTS).

All equipment will be designed and operated in compliance with applicable standards and regulations: pressure equipment (ESP), French "multifluide" decree (March 5, 2014), ICPE and SEVESO frameworks.

4.3.3 Hazard Identification

A simplified HAZID was conducted for the following phases: drilling, injectivity tests, injection (~3 months), shutdown and securing.

Major scenarios include:

- **Pipeline or surface installation leak:** CO_2 plume, oxygen-depleted atmosphere, cryogenic effects (dry ice), local environmental impact.
- **Loss of well integrity:** surface emission, subsurface migration, material embrittlement due to rapid cooling.
- **Overpressure/overfilling:** well and reservoir damages, leaks, induced seismicity.
- **Fire in compression station:** risks from auxiliary systems and domino effects.
- **Asphyxiating atmosphere / air quality:** accumulation in low points or poorly ventilated areas.
- **Natural earthquake:** excluded, very low risk in the area.

Table 7 present a summary of scenarios, causes, consequences, and main barriers are provided in this section. Some scenarios and consequences are further analyzed in Section 4.4 to classify them by impact and severity and to establish the detailed monitoring plan (Section 4.5).

Scenario	Causes	Consequences	Barriers
CO_2 pipeline or surface installation leak	Corrosion, welding defect, external damage, overpressure	CO_2 plume, asphyxiation, operational shutdown; dense cold cloud, cryogenic jets, solid projections (dry ice), local environmental impact (acidification)	Cathodic protection, compatible materials, sectioning valves, fiber-optic DTS monitoring, emergency shutdown, emergency plan, operating and work procedures
Loss of well integrity	Cement defects, aging, overpressure, external damage	CO_2 emission at surface, subsurface migration, dry ice formation, material embrittlement, localized asphyxiation risk, local environmental impact	Qualified design, CBL/VDL logs, downhole safety valve (SSSV), pressure/temperature monitoring, gas detectors, operating and work procedures
Overpressure / overfilling	Sensor failure, incorrect settings	Well & reservoir damage, leakage, induced seismicity	Redundant sensors, alarms, calibrated safety valves, operating procedures
Fire at compression station	Ignition source, ATEX non-compliance, electrical overload	Equipment damage, personnel risk, domino effects	ATEX zoning, fire detection, extinguishers, water curtains
Asphyxiating atmosphere (CO_2)	Localized leak, insufficient ventilation	Hypoxia, emergency evacuation	Fixed/portable CO_2 detectors, ventilation, Self-Contained Breathing Apparatus (SCBA) PPE

Table 7 : Preliminary Hazid assessment for the CO_2 pilot in the Paris Basin

4.3.4 Environmental, Social & Health Impact Assessment

An Environmental, Social & Health Impact Assessment was carried out in D4.8 (Canteli et al., 2026b) to evaluate potential impacts of the CO_2 injection pilot. Conclusions indicate that effects on physical, natural, and human environments would be low to very low. The Dogger reservoir, protected by impermeable geological layers, provides an effective barrier against CO_2 migration. Sensitive areas (watercourses, Natura 2000 sites) are not directly affected. Temporary nuisances (noise, dust, traffic) can be mitigated through appropriate avoidance and reduction measures.

4.3.5 Prevention and Control Measures

Risk analysis identifies prevention barriers (robust design, sensors, alarms) and mitigation measures (emergency shutdown, ventilation, evacuation).

To ensure safe CO_2 injection operations, the project developer must implement installations and technical devices to prevent incidents and protect people, assets, and the environment, in addition to design-integrated elements.

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Risk control equipment is included in the monitoring program detailed in section 4.5.

Prevention:

- Qualified design and compatible materials;
- Cathodic protection; redundant instrumentation and multi-level alarms;
- Operating and work procedures;
- Integrity checks (logs and tests); periodic inspections.

Detection:

- Fixed and portable CO_2 detectors in critical zones;
- Air quality monitoring;
    - Pre-alert: abnormal CO_2 increase (intervention, reinforced ventilation).
    - High alert: zone isolation and automatic equipment shutdown.
- Fiber-optic monitoring (DTS/DAS) on pipeline;
- Pressure/temperature sensors;
- Level/pressure sensors to prevent overfilling;
- Soil and aquifer monitoring.

Mitigation:

- hierarchical emergency shutdown;
- sectioning valves and calibrated relief valves;
- ventilation and evacuation;
- dry ice protection kits for interventions.

Human competence:

- risk-specific training.
- required certifications.
- regular emergency drills.
- feedback

4.3.6 Emergency management

Although CO_2 is neither flammable nor explosive, the plant's Internal Emergency Plan, or a new Emergency Plan depending on the location of the facilities, will need to include the pilot perimeter and address the following aspects:

- **Detection and alert:** CO_2 and fire detection systems, zone isolation, securing, compressor shutdown, pipeline isolation.
- **Personnel management:** evacuation and assembly, care for potential hypoxia victims (use of SCBA and oxygen therapy).
- **Organization:** on-call teams, coordination with public emergency services, scheduled drills.

The project will also be integrated into the Technological Risk Prevention Plan as confirmed in D4.8 (Canteli et al., 2026b), ensuring compatibility with urban planning control.

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4.4 Qualitative risk assessment of the CO_2 injection pilot

To establish the appropriate monitoring plan proposed for this CO_2 injection pilot in the Paris Basin, the corresponding project risks were assessed using the approach proposed within WP4 by REPSOL (Figure 12). This risk assessment approach is sequential:

1. Risk identification and qualitative analysis
2. Risk responses proposal and qualitative analysis

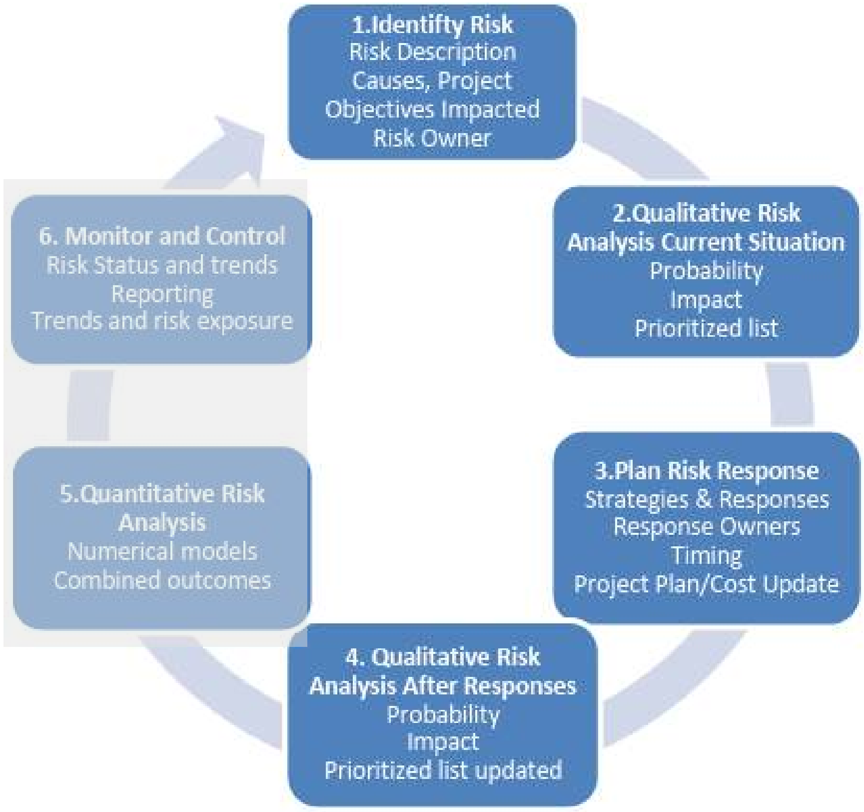

Figure 12 Qualitative risk assessment for a CO_2 injection pilot project in Paris Basin (based upon REPSOL Projects Risk Management Process). The shaded steps will not be implemented within PilotSTRATEGY WP4.

In the proposed approach, the risks and opportunities are managed together. All types of project risks are included:

- Technical
- Social
- Environmental
- Safety
- Legal
- Political
- Regulatory

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4.4.1 Risk identification and qualitative analysis

For each risk identified, there will be:

- Risk description and categorization
- Identification of potential causes triggering the risk event
- Identification of potential effects in case the event happens
- Select project “factors” where effects could affect
- Assign probability and impact to every factor considered, assuming no mitigation measures or corrective/preventive actions were taken.
- Risk severity is assigned considering the highest (worst case scenario)

The risk categories considered in the approach are shown in Figure 13 which the limits reported in Figure 14.

Political	Economic	Social	Technical	Legal	Regulatory and Permits	Environmental
Political and/or fiscal stability	Stakeholder alignment	Safety and security of personnel	Quality design basis/definition	Contract breach	Contract, JOA requirements	Sustainable development requirements
Legal framework for contract enforcement	Funding constraints	Community issues / Indigenous people	Experience operating in country	Disputes	Permitting Complexity	Environmental restrictions
Trade regulations and tariffs	Commercial agreements	Employment sourcing expectations	Climatic weather windows		Certifications	Disease control
Favored trading partners	Stability of currency Exchange rates	Civil disorders	Interface management		Decommissioning liabilities	Waste disposal
Taxation - tax rates and incentives	Quality of infrastructure	Local customs	Technical project complexity		Industrial safety regulations	
Political relationship with authorities	Skill level of workforce	Terrorism	Reservoir complexity, Subsurface		Environmental regulations	
Potential for nationalization of industry	Market availability of labor/materials	Working conditions	Severe fluid characteristics, flow assurance			
Current Embargoes	Inflation rates forecast, market escalation		Site conditions, Unknown bathymetry			
Complexity of establishing local presence	Local content requirements		Use of new technology			
			Conformance to codes and standards			

Figure 13 Risk categories (based upon REPSOL Projects Risk Management Process)

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Probability threshold

Probability				
Very Low	Low	Medium	High	Very High
Frecuency of Ocurrence (times/year)				
<1/100	1/100 - 1/10	1/10 - 1	1 -10	>10
% Description				
< 10%	10% - 40%	40% - 70%	70% - 90%	>90%
Event Description				
Remote chance of happening	May happens less than once during the BU/asset/project lifetime	Expected to occur in the BU/asset/project lifetime	Expected to occur several times in the BU/asset/project lifetime	Occur once or more per year in the BU/asset/project lifetime
Qualitative Description				
Rare, Very Unlikely	Unlikely but not imposible	Possible	Moderately Likely	Almost Certain, will probably arise

Impact threshold

Impact				
Very Low	Low	Medium	High	Very High
Cost (ABEX / CAPEX) (% of total investment)				
< 0,01	0,01 - 0,1	1 - 10	1 - 10	> 10
Schedule (% of project duration)				
< 0,5	0,5 - 5	5 -10	10 - 20	> 20
Operations (% of yearly budgeting)				
< 0,01	0,01 - 0,1	0,1 - 1	1 - 10	> 10
Reserves (%)				
< 0,01	0,01 - 0,1	0,1 - 1	1 - 10	> 10
Profitability (% NPV)				
< 0,01	0,01 - 0,1	0,1 - 1	1 - 10	> 10
People				
First Aid	Medical Aid	Lost Time	Disabling Injury	Fatality
Environment				
Fugitive emissions	Controlled released	Emissions exceed limits	Some damage	Widespread damage
Public Image				
Individual	Local	Provincial	Industry-wide	National/International
Qualitative Description				
Negligible	Minor, easily remedied	Moderate, some objectives affected	Major, most objectives threatened.	Most objectives will not be meet.

Figure 14 Threshold considered (based upon REPSOL Projects Risk Management Process)

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The descriptions of the various risks identified are provided in a Risk Register (see Annex 1 – Risk Register for a pilot in Paris Basin) and summarized in Figure 15. In the context of a pilot, no opportunity is identified as this is not deemed to be an industrial/business case.

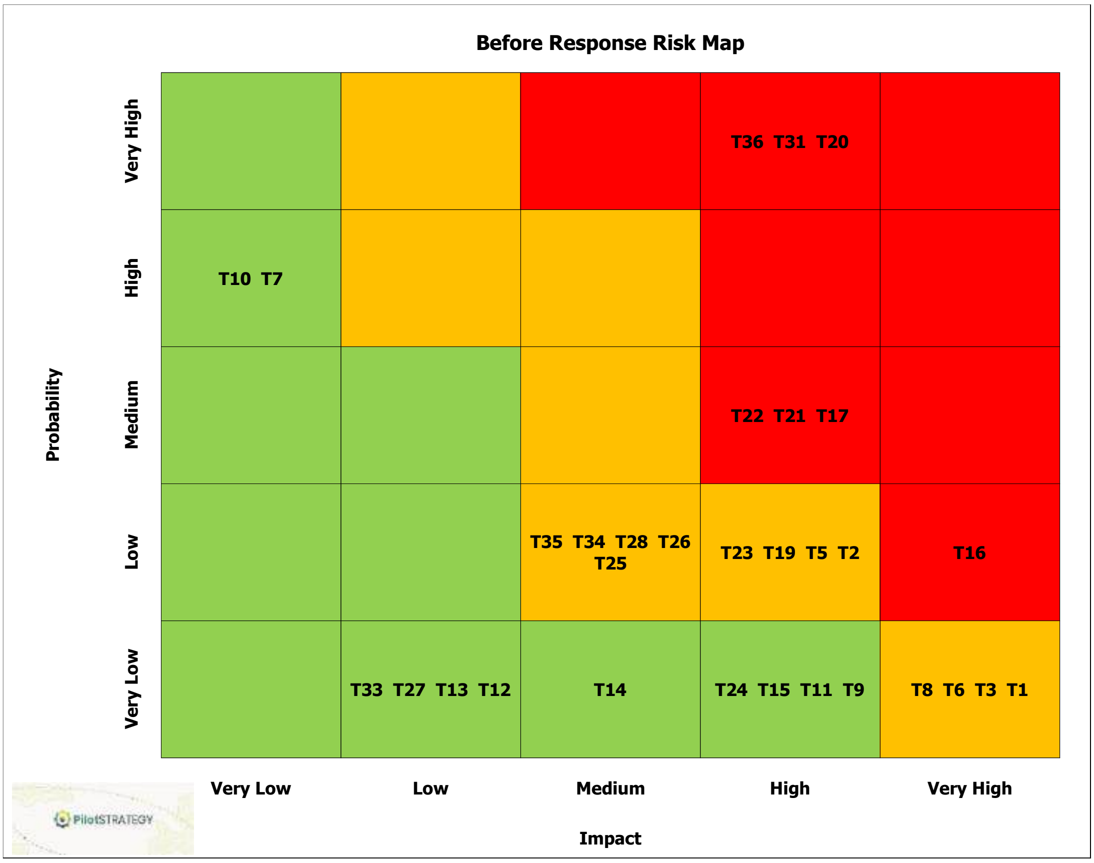

Figure 15 Risk identification and qualitative analysis for a CO_2 injection pilot project in Paris Basin

The critical risks identified are:

- T16: Uncertainty in CCS policy support or unexpected regulatory changes (policy context)
- T17: Delays or inability to obtain key permits (regulatory context)
- T20: Uncertainty in CO_2 supply (emitter context)
- T21: Public opposition or lack of social acceptance (societal context)
- T22: Ineffective risk communication with stakeholders (societal context)
- T31: Competitor securing acreage before pilot (legal context)
- T36: Access to EU/national funds (economic context)

The moderate risks identified are:

- T1: Vertical leakage through caprock (sealing deficiency) (technological context)
- T2: Vertical leakage along fractures (technological context)
- T3: Lateral leakage (technological context)
- T5: Leakage from operating well (technological context)
- T6: Leakage from legacy abandoned well (technological context)

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- T8: Induced seismicity (technological context)
- T19: Unexpected construction or operational cost changes (economic context)
- T23: Lack of maintenance or emergency procedures (environmental & safety context)
- T25: Unforeseen environmental impacts (environmental & safety context)
- T28: Mismatched performance between system components (capture, transport, storage) (technological context)
- T30: Local authority opposition despite national-level support (policy context)
- T34: Dense-phase CO_2 pipeline rupture near populated areas (safety and design implications) (technological context)
- T35: NZIA adopted by French authorities (regulatory context)

The low risks identified are:

- T7: Migration of formation brine outside expected boundaries (technological context)
- T9: Disruption by another activity (technological context)
- T10: Changes in groundwater flow, within the reservoir or in other layers of the storage complex (technological context)
- T11: Loss of Injectivity (technological context)
- T12: Lower than expected capacity (technological context)
- T13: Reservoir pressurization due to unexpected compartmentalization (technological context)
- T14: Accidental over-filling of the reservoir (technological context)
- T15: Uplift or subsidence of ground (technological context)
- T24: Corrosion or material issues in pipelines or wells (environmental & safety context)
- T27: Unexpected variations in CO_2 composition (technological context)
- T33: Lack of sufficient power distribution infrastructure for hub operations (technological context)

4.4.2 Risk responses proposal and qualitative analysis

The descriptions of the various risks identified are provided in a Risk Register (see Annex 1 – Risk Register for a pilot in Paris Basin) and summarized in Figure 16.

The remaining critical risks are:

- T16: Uncertainty in CCS policy support or unexpected regulatory changes (policy context)
- T17: Delays or inability to obtain key permits (regulatory context)
- T21: Public opposition or lack of social acceptance (societal context)
- T36: Access to EU/national funds (economic context)

These risks are mainly associated with the policy and regulatory context or the societal context which are beyond the scope of the pilot project and must be accounted for despite mitigation actions such as public engagement as proposed in WP6.

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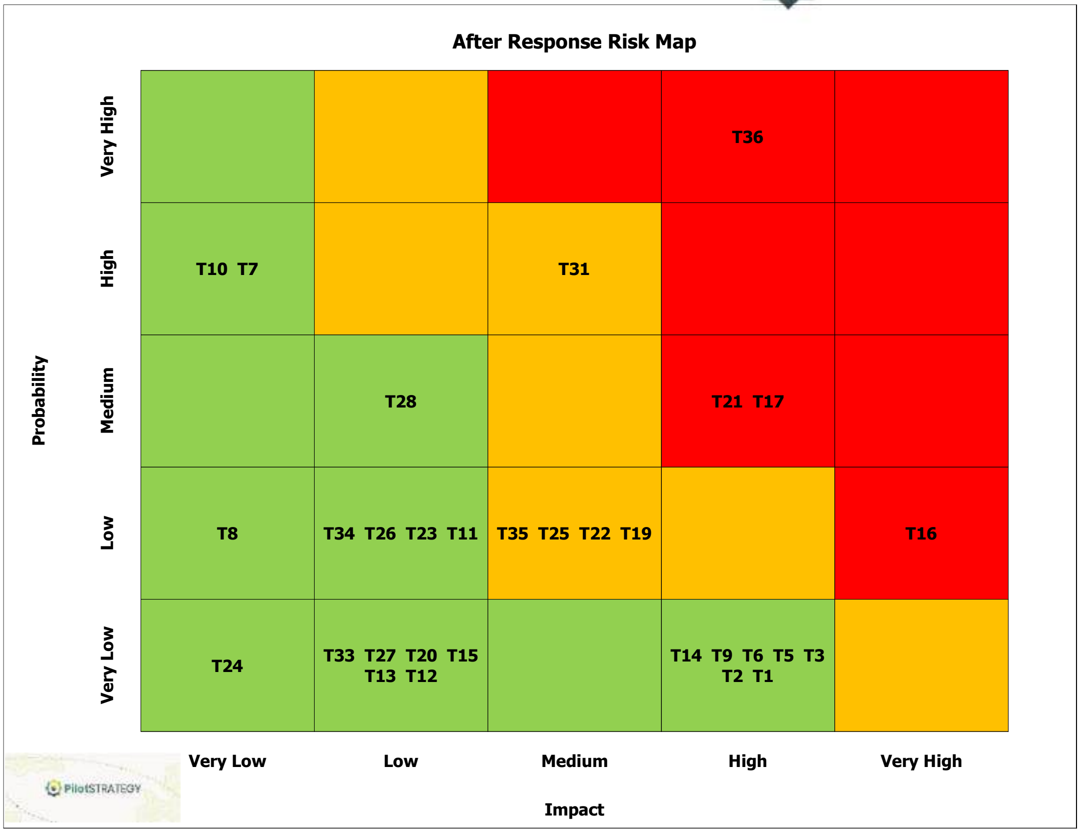

Figure 16 Risk responses proposal and qualitative analysis for a CO_2 injection pilot project in Paris Basin

The remaining moderate risks identified are:

- T19: Unexpected construction or operational cost changes (economic context)
- T22: Ineffective risk communication with stakeholders (societal context)
- T25: Unforeseen environmental impacts (environmental & safety context)
- T30: Local authority opposition despite national-level support (policy context)
- T31: Competitor securing acreage before pilot (legal context)
- T35: NZIA adopted by French authorities (regulatory context)

The mitigation and monitoring measures considered range from business negotiations (for T31) to local stakeholder engagement and project co-construction (T22) or rigorous industrial quality and health, safety and environmental processes (control, enforcement) and rigorous planning to prevent major delays (e.g. T19).

4.5 Risk-based monitoring plan

The monitoring plan foreseen to address and mitigate the identified risks will target different subsystems of the geosphere from surface level to storage level (Figure 17).

The monitoring plan was elaborated through a combination of tools from IEAGHG (2020), Quest project (e.g. Rowe et al, 2024), IOGP (2022), NETL (2017) and Geostock experience on gas storages

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which were applied to the context of the Paris Basin. The foreseen pilot will require monitoring the different compartments of the storage complex and beyond (Figure 17):

- Well: at well-head and in the well during and after the injection operations.
- Storage: to follow the development and stabilization of the CO_2 and pressure
- Subsurface/storage complex: impact on the water aquifer and seismicity
- Surface: impact on the ground level and pipeline

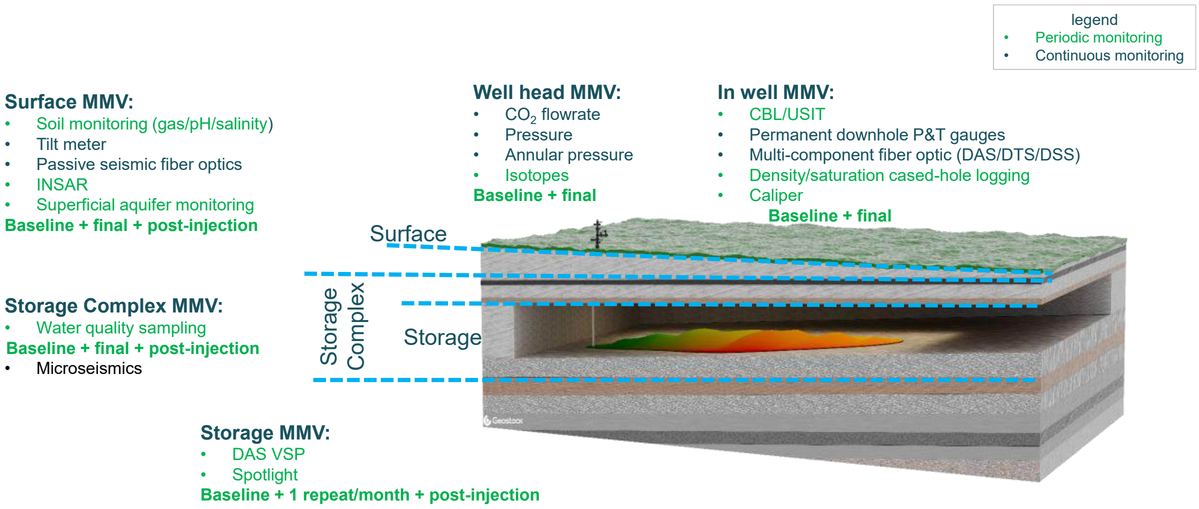

Figure 17 Monitored subsystems of the geosphere for a CO_2 injection pilot project in the Paris Basin

Depending on the technology used, the measurements will be permanent or periodic. For comprehensive monitoring, various techniques are needed combining continuous and time lapse since a leak may vary with time and might thus be missed by sampling-only techniques, and combining point measurements and wide areas, the latter due to the extent of injected CO_2 plume, and of overpressure field.

4.5.1 Monitoring plan and estimated costs

The estimated costs are obtained either from services provided or public literature. The commercial costs may differ from these estimates (Class IV: -30% to +50%) given the uncertainty level at this stage of the pilot. The annual inflation rate is assumed at 2.2% (D4.3, Canteli et al., 2025a). The cost estimates are reported in 2025 euros, assuming a parity exchange rate with dollars. The discount rate is 9% (D4.3, Canteli et al., 2025a). In the cost analysis most of the monitoring will appear as OPEX except when permanent installations are implemented, e.g. tilt meters, microseismic wells, fiber cable. The abandonment costs (ABEX) are estimated between 10 and 30% of the CAPEX (Bourgeois *et al.*, 2022).

The monitoring plan shall cover the injection and post injection periods after an initial baseline which is required for most monitoring techniques.

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4.5.1.1 Storage

Given the cumulative amount of injected CO_2 and its expected extension which are planned during the CO_2 injection pilot, the CO_2 monitoring in the storage will be carried out through 2 techniques, walk-away Vertical Seismic Profile combined with DAS/DTS acquisition and SpotLight™ acquisition, at the same frequency to minimize mobilization/demobilization costs of the seismic vibrator source. The cost for VSP acquisition range between 250 and 500 k€ per acquisition campaign including the vibrator source while the cost for Spotlight acquisition is between 35 and 65 k€ per acquisition campaign. This monitoring will be carried out while CO_2 is expected to be mobile.

In offshore environment, SpotLight™ acquisition could identify CO_2 during repeated campaigns after 2 kt and 4 kt of injected CO_2 (Al Khatib and Mari, 2024). This monitoring technique requires a baseline 3-D seismic acquisition to tune the parameters and a flow model to anticipate the location of the detection spots. In the foreseen monitoring plan, the SpotLight™ is combined with DAS/DTS VSP (*Abrouche et al., 2024*).

DAS VSP has been applied in several onshore projects such as Otway (Jenkins, 2020), Aquistore (White *et al.,* 2016; Cheraghi *et al.,* 2018) and shallow injection tests e.g. CAMI (Kolkman-Quinn *et al.,* 2023) and CSIRO (Jackson *et al.,* 2024). These DAS-VSP acquisitions were performed after various amounts of injected CO_2 not specifically targeting the estimated of the detection level. VSP was also applied for example at Hontomin pilot (Humphries *et al.,* 2016) and also at Frio pilot where it could detect the 1.6kt of injected CO_2 (Daley *et al.*, 2008). More recently (Kirstetter *et al.,* 2025), the Falaha CCS pilot identified a possible CO_2 detection after 1 month of injection, i.e. 1.5 kt, DAS VSP. Without any detailed design of the VSP acquisition, the amount of CO_2 that would be detected by DAS VSP is estimated at about 2 kt for the Dogger which is about 2% of the expected injection.

The DAS VSP enables better vertical resolution at the early stages of CO_2 injection compared to 3D seismic if the CO_2 does not spread too far from the injection well (Harvey *et al.*, 2022) which is the case for the considered injection pilot.

A site-specific design study of the DAS walk-away VSP monitoring for the injection pilot should be performed to refine this estimated amount. In particular, the location of the seismic vibration sources shall be consistent with the location from the 3-D seismic acquisition (Bordenave and Wallendorff, 2023) and account for the local constraints.

4.5.1.2 Storage complex

The main monitoring technique considered is micro-seismics through shallow wells equipped with permanent sensors. Such shallow wells will also be considered for water quality monitoring in sensitive (fresh water) aquifers.

The micro-seismic acquisition system is considered as CAPEX and will provide continuous recording of the stress changes within the overburden due to natural causes and injection pressure. Consequently, the micro-seismic acquisition will be carried out during the foreseen pressure monitoring. The cost ranges between 100 and 230 k€ including shallow well drilling and interpretation

The water sampling will be considered as included in OPEX and will be performed at the rate of CO_2 monitoring as shown in Figure 6. The cost is estimated between 20 and 30 k€ per campaign (adapted from Guinan *et al.*, 2024) based upon 10 samples per campaign.

4.5.1.3 Surface

The main monitoring techniques focus on the eventual impact of pressure such as Interferometric Synthetic Aperture Radar (INSAR), tilt meters and passive seismic, or the eventual impact of CO_2 such as soil (gas/pH/salinity) and superficial aquifer monitoring.

The passive seismic will require deployment of permanent fiber optic cables at surface which will thus be considered as CAPEX for the first acquisition while the following one, mainly requiring data interpretation will be considered as OPEX. The data interpretation will be carried out during the foreseen pressure monitoring as shown in Figure 6, its cost range between 45 and 60 k€ per campaign. Besides the DAS fiber implemented in the injection well, the local telecom fiber network may be used to complement the areal coverage (Figure 18).

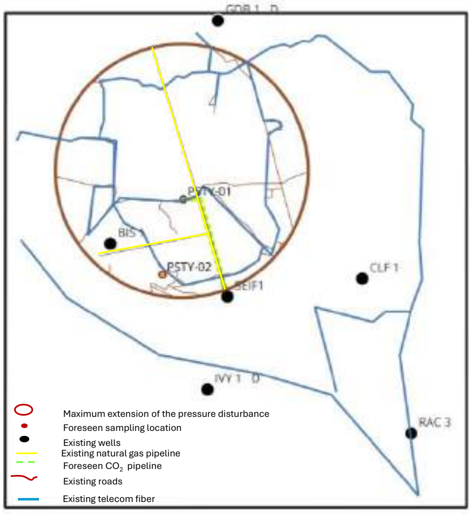

Figure 18: Existing telecom fiber network in the area of interest.

The INSAR acquisition is the only remote acquisition considered and will be carried out during the foreseen pressure monitoring as shown in Figure 6. Its cost is about 5 k€ per campaign.

The tilt meters will enable permanent measurements of ground motion and thus complement the INSAR acquisition. The deployment over the pressure footprint will imply about 8 stations which cost will be about 22 k€ which will thus be considered as CAPEX.

The soil gas monitoring will be performed at the rate of CO_2 monitoring as shown in Figure 6. The cost is estimated between 17 and 35 k€ per campaign (adapted from Guinan *et al*., 2024) depending upon the density of the measurements estimated between 1 point per 0.01 to 0.02 km².

Given the operational constraints and to avoid issues with agricultural lands, the proposed sampling is planned along the various road and pathways as illustrated in Figure 19 lead to 59 sampling locations within the 3-kilometre radius from the injection location in the storage formation which correspond to the expected pressure disturbance for the CO_2 injection pilot (DL 3.3, Chassagne *et al.,* 2024).

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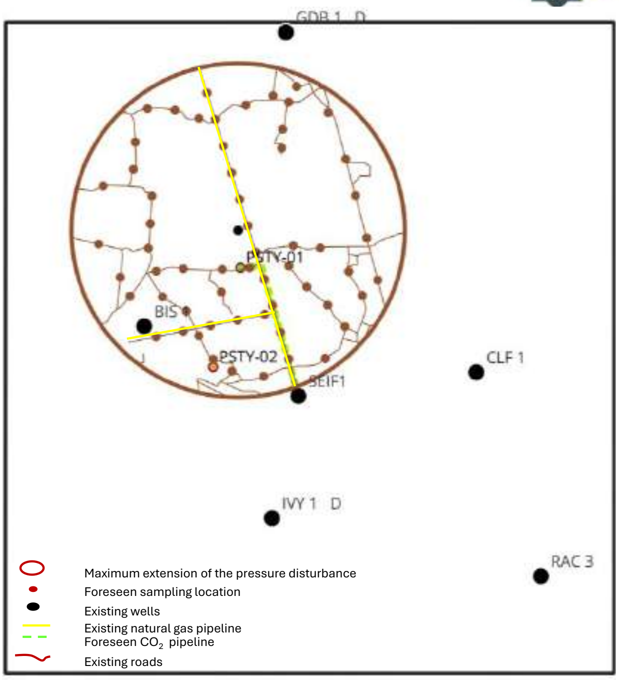

Figure 19: Foreseen soil gas sampling location in the area of interest.

To ensure safe operations around all surface installations, industrial CO_2 sensor will be implemented and complemented by atmosphere monitoring with lasers (Lidar or Open Path Laser). The costs are estimated at about 21 k€ (adapted from Guinan *et al*., 2024)

4.5.1.4 Well

There are several monitoring technologies that may be implemented in the well either at well-head or within the completion.

At well-head, the monitoring is rather standard for gas well e.g., pressure, temperature and flow rate gauges to monitor the CO_2 flux but also pressure monitoring of the various annulus. This standard monitoring might be completed by fluid sampling which might be remotely analyzed for isotopic composition.

The major cost items for well monitoring will be the downhole gauge for pressure and temperature which are considered as CAPEX for the well along with the wireline logging USIT/CBL and caliper which are planned during baseline. The USIT/CBL and caliper logs at the end of injection to verify the well and cement integrity are considered as OPEX. Their costs are estimated to be between 66 and 123 k€ for the J-shape well (PSTY-01) and 125 and 230 k€ for the long-deviated J-shape well (PSTY-02).

The in-well monitoring includes permanent downhole gauges for pressure and temperature and necessary well equipment such as nipples which cost is evaluated between 125 and 150 k€ considered as CAPEX. The fiber cable would incur costs between 150 and 240 k€ for the J-shape well (PSTY-01) and 280 and 440 k€ for the long-deviated J-shape well (PSTY-02) due to the different lengths of the wells and the required equipment such as clamps and well-head equipment. The installations costs are also included.

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4.5.1.5 Surface installations

To ensure safe operation at the plant, safety warning and metering equipment will be implemented.

The usual metering system will monitor the mass balance across the pipe which involves measuring input and output flow from the pipeline. This method may be affected by complex configurations (more than one inlet and one outlet) and by multiphase flows. In some application accuracy can be as low as 1% of total pipeline flowrate.

To further monitor the pipeline during operation a fiber optic monitoring system will be implemented. The DTS fiber will monitor signs of potential leakage in the CO_2 flowline by continuously measuring changes in temperature for real-time monitoring of the CO_2 flowline (*Richards et al.*, 2022). The pipeline between the plant and well head will be equipped with sectioning valve to minimize any accidental release.

4.5.1.6 Planning

The monitoring will be carried out while CO_2 is expected to be mobile and pressure disturbances are significant.

From WP3 results, the pressure disturbances will disappear in about 8 months (DL 3.3, Chassagne *et al.*, 2024). The planning shall be extended, if necessary, as a function of results from the long-term simulations carried out in WP3 for the mobile CO_2. From the long-term modeling results carried out in WP3, the CO_2 is still slowly migrating upward towards the caprock beyond the pressure vanishes (D3.4, Ben Rhouma *et al.*,2025). The monitoring must be carried out until the CO_2 plume is stabilized or no longer detectable to meet the implementation of the CCS directive within the French regulation[1]. To estimate the minimum monitoring period, the two criteria were used to filter the numerical results from WP3 (D3.4, Ben Rhouma *et al.*,2025):

- Saturation criteria: Identify cells where the gas is appearing at a given time i.e. the gas saturation increases above a detection limit assumed at 5%.
- Detection criteria: identify cells where the mass of CO_2 is above the detection level of the monitoring technics which are estimated to be about 2 kt (see 4.5.1.1).

Considering the above criteria, the modeling results for the long-term evolution of the pilot injection are filtered as shown in Figure 20. No further migration of CO_2 is modeled beyond 8 years after the end of injection when the last cell invaded by CO_2 is above the detection level (criteria 2 in Figure 20)

In Figure 21, the CO_2 monitoring is carried out for 8 years post injection. The frequency of the monitoring differs between injection and post injection periods for periodic measurements (Figure 17):

- Monthly during injection period
- Geometric progression during the post injection period

Before the injection period, a baseline measurement period is assumed while the surface installations, e.g. pipeline and compression plant, are commissioned. Well drilling and construction and surface

1 https://www.legifrance.gouv.fr/codes/section_lc/LEGITEXT000006074220/LEGISCTA000022093745/#LEGISCTA000022096095

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installation long lead item durations are estimated based upon the current French market procurement lead time.

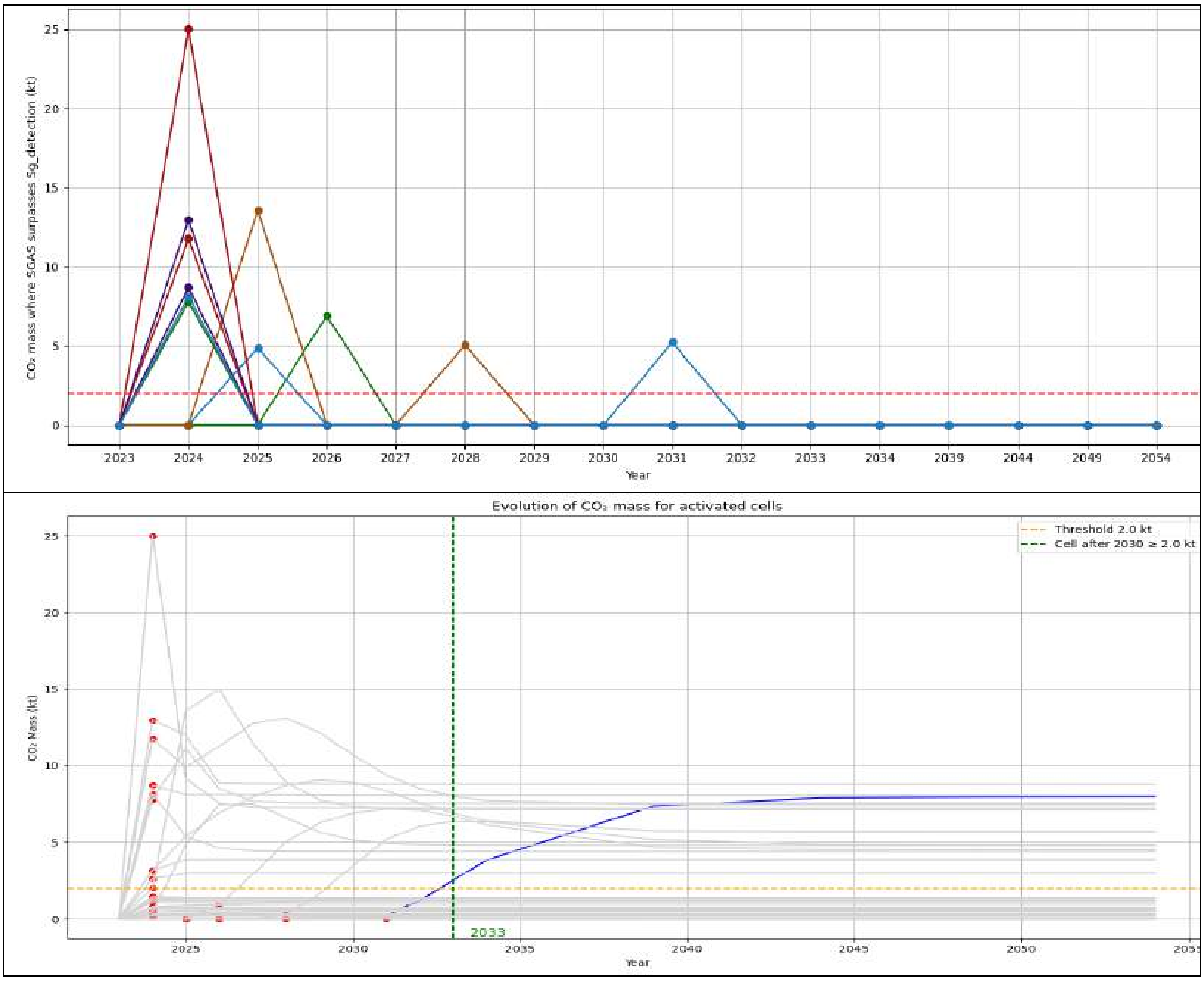

Figure 20: Mass of CO_2 in the cells where CO_2 is migrating assuming a pilot injection in 2024: Saturation criteria (top), detection criteria (bottom)

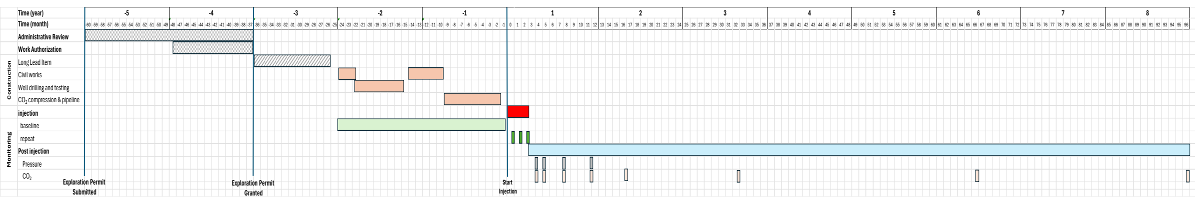

Figure 21: Foreseen life cycle planning for a CO_2 injection pilot from administrative filing to post injection monitoring.

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5. Ebro basin

The CO_2 storage project in the Ebro Basin proposes the full life 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 Ebro Basin proposal is focus on storage phase, being CO2 capture and CO2 transport outside of this work.

5.1 Injection well

5.1.1 Well design. Drilling and completion.

The document provides and overview of the well design chosen to perform CO_2 injection in the Ebro basin. This well design is intended to be a preliminary version of an injection well to inject CO_2 that will target the Buntsandstein fm. that is part of the strategic territories in Europe for the implementation of Carbon Storage in underground reservoirs. The objectives are to:

• Conduct all operations with full regards to personnel safety, ensuring that the program is conducted with zero lost-time incidents (LTI) and in an environmentally responsible manner to minimize the impact of operations on the local environment.

• Gather reliable data necessary for geological and reservoir evaluation through wireline logs. Evaluate the Potential for CO_2 injection of the Buntsandstein Formation (Lower Triassic sandstones with irregular detrital sedimentation) with sufficient and reliable data.

• Preliminary time and cost estimates for such a project.

5.1.1.1 Offset well analysis

There are several offset wells in the area. All were looking for hydrocarbon evidence in the Jurassic and Triassic and were abandoned with cement plugs.

Well	Company	Year	TD (MD m)	Operation days
MONEGRILLO-1	N/A	1958	1446	45
BALLOBAR-1	ENPASA	1961	3450	239
FRAGA-1	ENPASA	1962	2143	117
CADASNOS-1	ENPASA	1963	1550	51
SARIÑENA-1	ENPASA	1963	2893	137
TAUSTE-1	ESSO	1963	3329	76
CASPE-1	AUXINI S.A.	1973	1810	52
EBRO-1	CAMPSA	1976	1970	83
EBRO-2	CAMPSA	1977	2950	148
MAYALS-1	CAMPSA	1979	1401	37
LOPIN-1	CAMPSA	1981	1652	61

Table 8 Offset wells

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Some had production test (DST's) and cores even though only 1 of these cores remain. These are old wells drilled from 1958 to 1981 as can be seen from the table below (Table 9).

Main drilling hazards observed from offset wells:

- From DST data indicate that numerous wells show Water Hydrostatic Pressures which may indicate hydraulically communication with surface formations. Closest wells to the injection site show some overpressure (Ebro 1&2, Monegrillo) in the Buntsandstein fm.
- Mud losses reported in various formations, that are frequent to very frequent in Cretaceous/Jurassic and Muschelkalk formation.
- Stuck Bottom Hole Assembly (BHA) and tight spots. These events are mostly related to clay swelling and bit balling.
- Cavings are being reported as well as some collapse of clay formations.
- Multiple bits to drill a TD section (Tri-cones have a rotation limit that do not apply to PDC bits) not related to fm abrasiveness.
- There is little info regarding logging operations, in some cases tight hole prevent the wireline tool to reach TD. No differential sticking/fishing operation has been reported
- No wells needed sidetrack to reach TD, no gas/fluid kicks or influx were reported, and no Bottom hole BHA was left in hole.

Well	Mud Losses	Drill string problems	Hole Problems
MONEGRILLO-1	?	DP wash out at 1218, 1359 and 1567 m	N/A
BALLOBAR-1	Mud losses 675–1040; 2651 Total mud losses: 1526, 1007	Lost cones 2886 and 2889	Cavings 1526–1528 (Jurassic) Keuper cavings (1880–1990 m) Tight hole 2238–2246 (Muschelkalk) BHA stuck at 158 m (Quaternary?) Lost cones 1935 m
FRAGA-1	Total mud losses: 575 m; 1185 Mud losses: 1493; 1550; 1680; in Buntsandstein	N/A	Swabbing Muschelkalk for production data (H_2S suspected presence, rotten eggs smell) BHA stuck at 2089 m (Paleozoic)
CADASNOS-1	Mud losses at 744.8 m	N/A	Tight hole at 418 / 744.8 (Tertiary) Tight hole at 975, 1087, 1324 m (Tertiary–Cretaceous–Jurassic) Tight hole at 1517 m (Jurassic)
SARIÑENA-1	Mud losses at: 1998, 2285, 2349, 2809, 2831, 2841, 2850, 2886	N/A	N/A
TAUSTE-1	N/A	Paleozoic from 1245 m, strong deviation increased due to extreme hardness in the sandstone that produced torsion augmentation and several breaks in the drillstring with successful fishing operations	N/A

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CASPE-1	N/A	N/A	Between 500 and 650 m (red clays) big cavings were produced in the upper Buntsandstein Tight hole between Muschelkalk and Buntsandstein
EBRO-1	Mud losses at: 1425 and 1502; 600 l/h (Muschelkalk)	BHA lost at 549 m	Tight hole in 17 ¼" section
EBRO-2	From 2094 to 2400 m mud losses (MV: 1.42 g/cm³) Mud losses: 1560 m; 2139 m; 2230 m; 2325 m; 2575 m; 2640 m; 2704 m	Lost cones at 2325 m (Muschelkalk) BHA stuck at 2509 m (Muschelkalk)	Well collapse, BHA stuck at 1912 m (Keuper?) Tight hole: 2620 m (Muschelkalk)
MAYALS-1	N/A	Some HWDP wash outs	Tight hole at 222 m Bit balling at 306 m BHA packed with swelling clays at 976 m (Tertiary)
LOPIN-1	N/A	DP wash outs at 1218; 1359 and 1567 m	N/A

Table 9 Drilling events

5.1.1.2 Well design

The well base case design is based on most likely case pore pressure and fracture gradient that was completed for task 3.2 1D Geomechanical Modelling. Figure 22 shows fracture gradient & pore pressure profiles for the planned injector well.

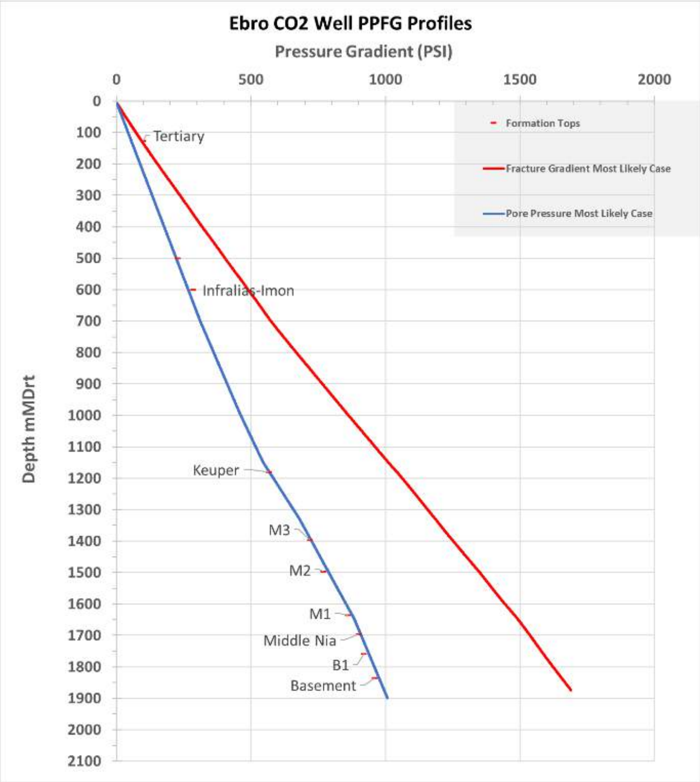

Figure 22 Pore pressure & Fracture gradient for proposed injection well

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For the base case design, the well would be drilled in 4 sections, and the reservoir will be drilled in 8-1/2" hole. This well is planned as vertical well and the casing string comprises of (Figure 23):

- 20" conductor casing to be set at 30 m TVDRT and cemented to surface, to provide the structural support needed for the installation of the diverter system. This section will be drilled with a 26" Bottom Hole Assembly (BHA).

- 13-3/8" surface casing to be set at ~1,179m TVDRT in the lower Liassic- Imón formation to drill the tertiary shales and Liassic silts with a shale inhibitor water-based mud (WBM) that will minimize clay swelling and all drilling problems related to it. This section will be drilled with a 17-1/2" BHA and cemented to surface.

- 9-5/8" intermediate casing to be set at ~1,720m TVDRT, above Buntsandstein B1 and B2. This section will be drilled with a salt/brine saturated WBM to allow for a correct drilling of the Keuper evaporites section. This section will be drilled with a 12-1/4" BHA and cemented to surface with a special cement slurry to be more resistant to CO_2 related acidic environment.

- 7" liner will be set at section TD planned at 2,000m TVDRT. This section will be drilled with an 8-1/2" BHA and it will use a WBM like Clay Free KCL Polymer to minimize damage to the Buntsandstein B1 and B2 formations and not compromise the injectivity test.

The proposed wellhead is a conventional one with:

- Section A (Casing Head Housing): 20 ¾" 3k x 20" Slip on lock
- Section B (Casing Head Spool): 13 5/8" 5k x 20 ¾" 3k
- Section C (Casing Head Spool): 13 5/8" 5k x 11" 5k

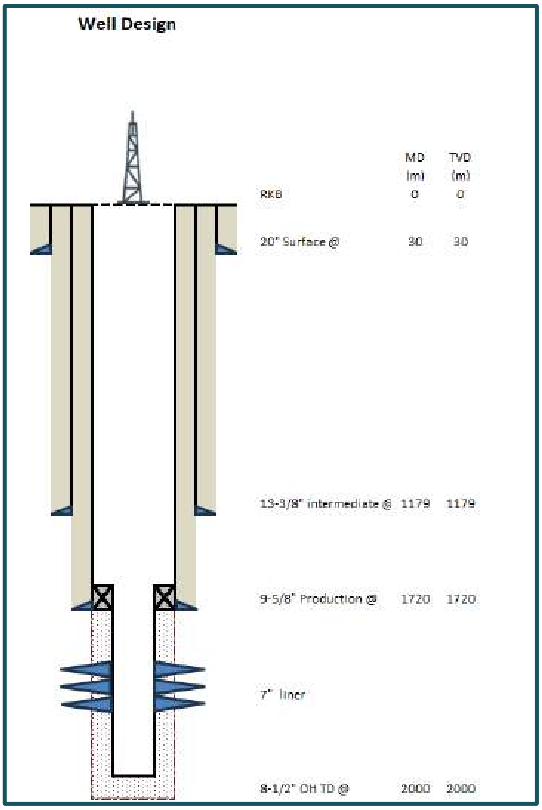

Figure 23 Injection well scheme

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The well design proposed and materials are conceptual and require full engineering once pre-drill data is available.

5.1.1.3 Well Time & Cost

Well timings are based on the most likely case (P50). The following assumptions were made to provide this Time & Cost (T&C) estimate:

- A 1,000 hp capacity drill rig is considered for drilling these well as its capabilities are well within the well design proposed.
- International mobilization costs 3MM USD (2.76 M€), and 45 days based on previous estimations. A mobilization within the same country has a lower cost however it is unlikely that there is an opportunity to find a rig of these capabilities in Spain. For demob. cost 1MM USD (0.92 M€) is assumed.
- The daily rig rate is based on Repsol similar projects and a query to procurement department.
- Well, injectivity testing service is included for the well AFE.
- Based on the offsets wells, a mechanical well design is proposed with casing: 20 (conductor)''; 13-3/8'' (superficial); 9-5/8'' (intermediate) and 7'' liner in the production section.
- Steel selection L-80 for all casings with exception of the 7" production liner that will be a special material (Superchrome 13 or 20Cr super Duplex) to withstand the integrity in such a corrosive environment typical of a CO_2 injector well.
- Conventional coring is expected to be cut in the Lower Triassic facies. For core time estimation actual coring operations times are being used from onshore exploration wells.
- Special Cement Slurry is required.
- If the injectivity test is positive and the well will become a keeper, then it is proposed a liner tie-back to surface and the completion to be run in 3-1/2” tubing. This operation might be done at a later state, and a workover rig can be used. Therefore, the cost is not included in this T&C estimate.
- No T&C is estimated for the Pad preparation and all civil works associated with it.
- For Project Management 500K$ (460K€) is assumed.
- For Non Productive Time (NPT) 15% is considered which industry standard is considered in normal environments such as this one. On top of that, 20% contingency is also considered.
- The Wireline data acquisition cost is estimated by the Operations Geology team in Repsol (Figure 24).

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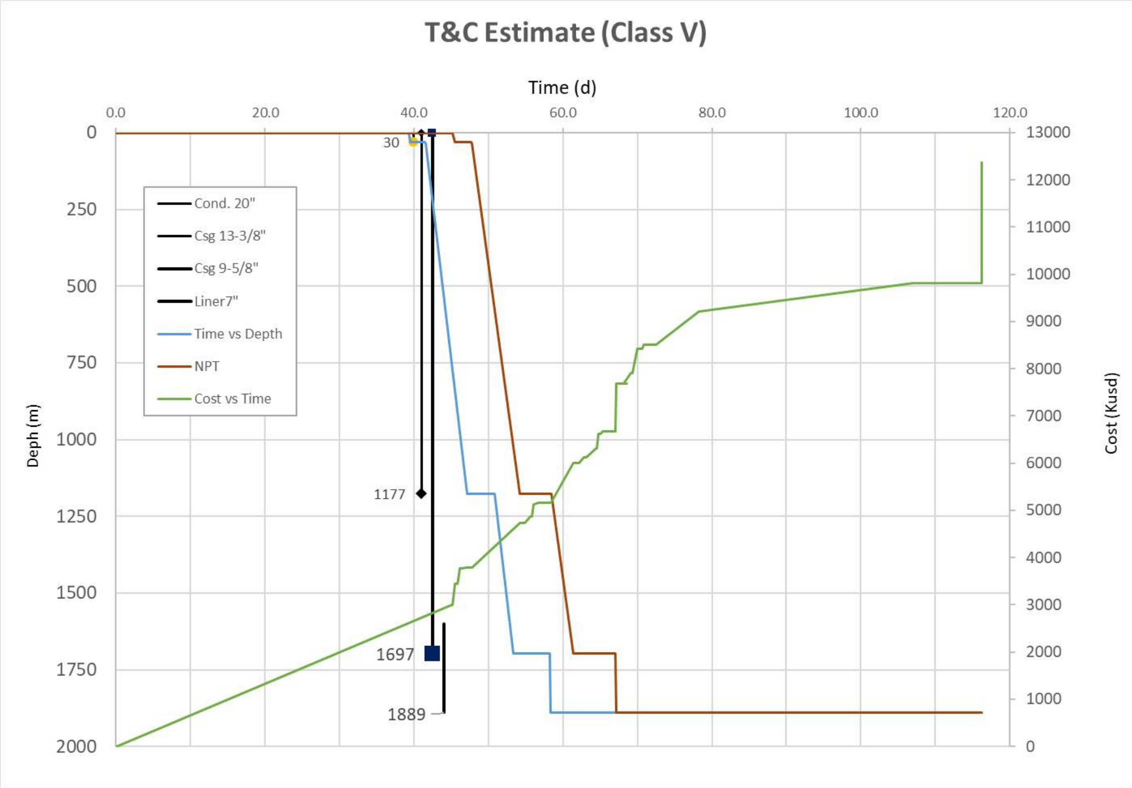

Figure 24 Injection well time & cost estimate

- For the P&A the following assumptions apply (Figure 25).
  - The well is assumed to be permanent plug and abandonment (P&A) for the base case. The P&A assumes good cement behind 9-5/8" & 13-3/8" casings. The abandonment will follow Repsol's criteria - 20-00080PR - V1.0:
  - **Liner perforated intervals**:
    - Cement squeeze on perforations.
    - 50m cement plug above perforations w/ cement retainer
  - **Liner Top**:
    - 50m cement plug set inside 7" liner
    - 100m cement plug settled above liner hanger.
  - **Wellhead Removal**:
    - 100m surface plug placed up 100m below ground.

      In case the well becomes a keeper, P&A cost and time would be drastically reduced to a temporary P&A for future re-entry. For a success case and a temporary abandonment 6 days is assumed as estimated time.

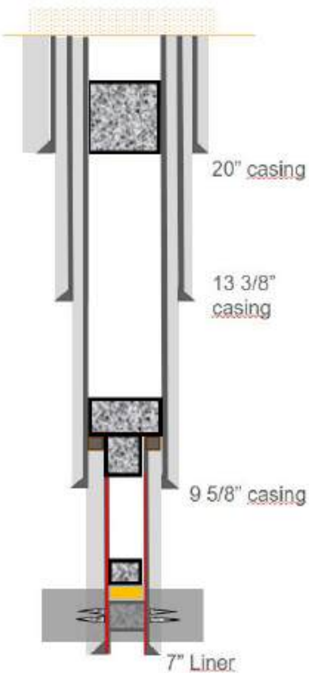

Figure 25 Well abandonment diagram

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The total days with 15% of NPT are 116.3 days and the total cost is 12.384MM USD (10.775 MM€) for the drilling, injectivity test and the P&A with the assumptions stated above (Table 10).

Section	Depth (m)	Duration (d)	Cum. Duration (d)	Cum. Cost (k€)
Mobilization	0	45.0	45.0	2610
Drill 26"	30	0.7	45.7	2992
20" Conductor	30	2.1	47.8	3295
Drill 17 1/2"	1179	7.0	54.8	4113
13 3/8" Surface	1179	3.6	58.5	4507
Drill 12 1/4"	1720	3.4	61.9	4507
Open Hole WL logs	1720	1.4	63.3	5235.76
9 5/8" Intermediate	1720	4.0	67.2	5987.92
Drill + Coring 8 1/2"	2000	3.4	70.6	6873.28
Open Hole WL logs	2000	1.7	72.3	6891.94
7" Liner (prod)	2000	2.6	74.9	7417.13
Injc. Test	2000	6.5	81.4	8028.55
P&A	2000	25.0	106.4	8547.74
DEMOB + CONTINGENCY + PROJECT MANAGEMENT	0	9.9	116.3	10775

Table 10 Drilling and other associated costs

5.1.2 Well operations.

5.1.2.1 Summary of Well permits roadmap.

This roadmap provides a simplified and operational view of the permits required for the development of CO_2 storage wells in Spain, in the Ebro Basin located in Aragón province. It reflects the regulatory pathway for investigation (including seismic and exploration wells) and exploitation (injection wells & surface facilities).

1. Initial Step – General Investigation Permit (Mandatory Starting Point)

1.1. Permit of Investigation

The project must begin by obtaining an investigation permit from the Dirección General de Energia y Minas. This permit grants the exclusive right to investigate the storage potential of the geological formation and is the legal prerequisite for all subsequent field activities (seismic, drilling, etc.).

Key aspects:

- Validity: 4 years, extendable twice in 2-year intervals (max 8 years).
- Declares public utility of required land (enables temporary occupation/expropriation).

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- Requires: plan of investigation, competence documentation, coordinates of the project as well as technical documentation.

Once the general investigation permit is granted, the operator can follow the next mandatory procedural steps.

1.2. Communication & Planning Obligations

1.2.1. Notification of Start of Works & Appointment of Director Facultativo.

1.2.2. Submission of Annual Work Plans. These are statutory commitments under mining law for any investigation activity.

1.3. Seismic Campaign Permits

Only required if 2D/3D seismic acquisition is part of the investigation program (not applicable to the project).

1.4. Drilling of Exploration Wells Permits

This are all required permits to drill an exploratory well to test the potential injectivity for a CO_2 project

1.4.1. Land Access & Urban Planning Permit

- Land occupation rights (private agreement or expropriation procedure).
- Municipal construction license.
- Authorization for special use in non-urbanizable land, supported by environmental procedures.
- Cultural authorization if near protected heritage assets.

1.4.2. Drilling Authorization

- Authorization from Dirección General de Energía y Minas.
- Requires a full drilling project, equipment description, and safety documentation (ITC 06.0.01).

1.4.3.Environmental Impact Assessment

2. Exploitation Phase permits

2.1 **CO_2 Storage Concession**

- Requested to the Subdelegación del Gobierno (Area of Industry & Energy).
- Granted by MITECO.
- Requires: site characterisation, project of exploitation, monitoring plan, corrective measures, post-closure plan, financial guarantee, etc.
- Conveys public utility for permanent land occupation

2.1.1 Full Environmental Impact Assessment. The environmental declaration applies also to the planned injection wells and all related activities to the drilling of these wells & surface facilities for the CO_2 injection.

2.2 **Execution Permits for Injection Wells**

2.2.1 Authorization for drilling Injection Wells

2.2.2 Includes both new wells and adaptation of existing exploration wells to permanent injector wells.

2.2.3 Requires a complete drilling/Completion/Workover project following safety standards.

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2.3 Land Occupation & Urban Planning (B.2.2)

- Similar to exploration wells, but under storage concession conditions.
- Municipal licenses + Special Use Authorization in non-urbanizable land.

3. Planning & logistics of well operations.

During the operations a base will be needed. The function, scope, and operational importance of the Logistics Warehouse designated to support the upcoming land drilling campaign. The warehouse/base constitutes a critical component of the campaign's material management system, ensuring that all drilling activities are supplied in a timely, safe, and cost-efficient manner. It provides a centralized hub for inventory control, material inspection, logistical coordination, and emergency response capability, thereby safeguarding continuity of operations and minimizing non-productive time (NPT).

Given the remote nature of the wellsite and the lack of spares as Spain is non an oil & gas, operational success relies on maintaining a reliable stock of equipment, tubulars, consumables, drilling fluids & additives, and service-company materials. The Logistics Warehouse serves as the central platform from which these materials are received, inspected, stored, prepared, and dispatched according to the drilling schedule. The main functions of a base are as follows:

a. Inventory Management and Control

The warehouse maintains controlled stock levels for all equipment and consumables required for drilling and completion operations.

- Storage of casing, tubing, wellheads, drilling tools, spare parts, equipment, and chemical supplies.
- Use of standardized inventory management systems to monitor stock levels and material movements.
- Regular cycle counts, audits, and shelf-life tracking to ensure availability of critical items.
- Segregation of hazardous materials in accordance with applicable regulations.

This function ensures that the wellsite receives the correct materials at the correct stage of drilling without delays.

b. Material Reception, Verification, and Quality Assurance

Upon arrival from vendors or service companies, all materials undergo documented inspection processes to verify compliance with the specifications of the drilling program. These processes include:

- Dimensional and visual inspections of tubulars and equipment.
- Documentation review (certificates, test reports, MSDS, calibration records).
- Non-conformance identification and quarantining of suspect materials.
- Quality assurance procedures to maintain full traceability.

This ensures that only compliant and certified materials enter the supply chain for field use.

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c. Transportation Coordination and Dispatching

The warehouse coordinates all inbound and outbound trucking activities associated with the drilling campaign. Responsibilities include:

- Scheduling of transport to wellsite based on drilling progress and operational priorities.
- Compliance with transport regulations, including hazardous materials, road permits, and axle load limitations.
- Management of backload materials returning from the wellsite, including used tools, waste containers, and equipment needing inspection.

This coordination ensures safe and efficient movement of materials throughout the campaign.

d. Operational Support and Emergency Response

The warehouse maintains an inventory of critical spares and high-impact materials to support unplanned operational events. Staging of contingency equipment required for well control, stuck pipe scenarios, or hole-cleaning issues. Serves as coordination center in case of an emergency.

e. Waste Management and Reverse Logistics

In alignment with environmental and regulatory requirements, the warehouse manages the backhaul and segregation of waste materials, including:

- Drill cuttings containers, used chemical drums, scrap metal, and disposable materials.
- Segregation and documentation in accordance with waste-management regulations and company procedures.

This ensures compliance with environmental standards and responsible handling of waste streams

The Logistics Warehouse plays a vital role in the successful execution of the land drilling campaign. It ensures that material, equipment, and consumable requirements are met in a timely, controlled, and safe manner while maintaining compliance with all regulatory and partner-agency expectations. Through standardized processes, quality assurance, and effective coordination of transportation and vendors, the warehouse supports the continuity, efficiency, and integrity of drilling operations

When drilling operations begin the base shall be operative 24/7. The base shall have a crane and a forklift as minimum lifting equipment.

5.1.2.2 Summary of Well logging, coring and testing plan

The following table outputs the logging program design. Main activities, logging velocities & time are listed (Table 11).

Activity	Speed (m/h)	Time (h)
REAMING TRIP – hole conditioning		**10**
Run 1.a		
R/U (Rig Up)		3
RIH (Run in hole)	3048	0.56
Spectral GR, ND, CALI + FMI, DT, RES	240	2.25
POOH (Pull Out of hole)	3048	2.59

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R/D (Rig Down)		3
Run 1.b		
R/U		3
RIH	3048	1.77
SWC	50 swc / 15 mins / swc	10
POOH	3048	0.39
R/D		3
REAMING TRIP – hole conditioning		**10**
Run 2.a		
R/U		3
RIH	3048	0.6
Spectral GR, ND, CALI + FMI, DT, RES	240	0.48
POOH	3048	0.56
R/D		3
Run 2.b		
R/U		3
RIH	3048	0.6
NMR (Nuclear Neutron Magnetic Resonance)	180	0.64
RFT + MDT	20–30 pts / 15 mins / pt	7.5
POOH	3048	0.49
R/D		3
Run 2.c		
R/U		3
RIH	3048	0.49
SWC	50 swc / 15 mins / swc	12.5
POOH	3048	0.6
R/D		3
Subtotal Run 2		**92.03**
CBL	3 sections × 24 h	72
VSP	24 h	24
TOTAL LOGGING TIME		**188**

Table 11 Well logging program for the injection well

List of acronyms and explanations.

General operations

- REAMING TRIP – Hole conditioning trip (reaming to clean and stabilize the wellbore)
- R/U – Rig Up
  Installation and setup of wireline equipment on the rig.
- R/D – Rig Down
  Dismantling and removal of wireline equipment from the rig.
- RIH – Run In Hole
  Running the wireline toolstring into the well.
- POOH – Pull Out Of Hole
  Retrieving the wireline toolstring out of the well.

Open-hole logging

- GR – Gamma Ray
  Measurement of natural radioactivity for lithology and correlation.
- Spectral GR – Spectral Gamma Ray
  Gamma ray measurement separated into potassium (K), thorium (Th), and uranium (U).
- ND – Neutron Density

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Combined neutron and density logs for porosity and lithology evaluation.

- CALI – Caliper Log
  Measurement of borehole diameter to assess hole condition.
- DT – Delta-T / Sonic Log
  Acoustic travel time measurement used for elastic properties and geomechanics.
- RES – Resistivity Log
  Electrical resistivity measurement used to evaluate fluid saturation.
- FMI – Formation MicroImager
  High-resolution electrical image of the borehole wall for fractures, bedding, and stress analysis.

Sampling and testing

- SWC – Sidewall Core
  Small rock samples taken from the borehole wall for laboratory analysis.
- NMR – Nuclear Magnetic Resonance
  Log used to determine pore size distribution, effective porosity, and permeability indicators.
- RFT – Repeat Formation Tester
  Wireline tool for formation pressure measurements.
- MDT – Modular Formation Dynamics Tester
  Advanced formation testing tool for pressures, mobility, and fluid sampling.

Cased-hole logging and seismic

- CBL – Cement Bond Log
  Log used to evaluate cement quality and zonal isolation behind casing.
- VSP – Vertical Seismic Profile
  Borehole seismic survey for time-depth calibration and seismic tie.

5.1.2.3 Injectivity test

A water injection test shall be planned in the Pilot project well (Buntsandstein fm). Based on the Dynamic model the P50 maximum storage capacity is 14.90Mt and an optimal storage of 14.62Mt with an optimal rate of injection of 0.254 Mt per year and per well.

A positive test would mean this well can potentially inject the equivalent of 0.254 Mt which translates into 372.5 ksm3/d of CO2 equivalent to ~1918.4 sm^3/d of fresh water (ref: fresh water FVF= 1.0 v/v & CO2 FVF @100bar = 0.005150 v/v)

Well test objectives:

- Initial reservoir pressure & temperature
- Well performance (injectivity) in the zone to test
- Completion evaluation: wellbore skin factor (S)
- Formation transmissibility: kh
- Formation or fracture parting pressure (FPP)
- Formation brine sample (fluid characterization & flow assurance)
- Optional: Distance to boundaries (Radius of investigation)

There are various types of tests that can be performed. It depends on the above-mentioned objectives which will need to be designed according to the level of knowledge & uncertainties of the field (geology, fluids & reservoir properties). It is assumed this test will be limited to the Buntsandstein formation (1760-1835m MD). The main types are:

- **Multi-rate test**: injectivity; completion evaluation (mechanical skin & rate dependent skin).
- **Fall-off test**: wellbore storage (WBS), skin, formation permeability, reservoir anomalies identification (fractures, crossflow, ...) and reservoir boundaries (faults, unconformities, pinch-outs…).
- **Step-rate test**: formation or fracture parting pressure (0.5-0.6 psi/ft fracture gradient estimation, injectivity; completion evaluation (mechanical skin & rate dependent skin) and formation permeability.

Next is an example of possible sequence of tests to achieve the proposed objectives (Figure 24).

1. Step rate test: 1st series of injection step rates (increasing), remaining into matrix condition.
2. Fall-off test(1st): well shut-in
3. Step-rate test: 2nd series of injection step rates (increasing), exceeding fracture parting pressure.
4. Fall-off test(2nd): well shut-in (characterize fracture created and effect to reservoir permeability)

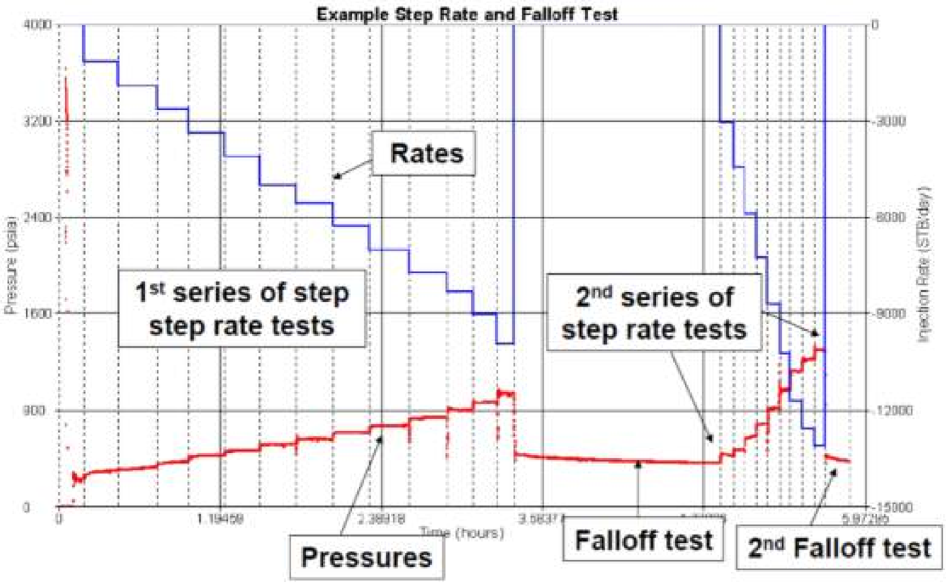

Figure 24 Example of possible injection test sequence

In all cases the test must reach radial flow during both injection and fall-off periods. This requirement is the basis for Pressure Transient Analysis (PTA). As part of the injection test design specifications a few considerations are important in the overall planning.

- Well clean-up: to reduce skin
    - Well unloading likely requiring N2 lifting (reservoir @ hydrostatic conditions) – CT unit.
    - Waste storage capacity to accommodate 2 wellbore volumes (flowback) for each tested interval.

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    - Well acidizing: to stimulate the formation (needs to be studied if it gives any benefit).
    - Acid wash (spot acid via CT or DP).
- Well completion: for the purpose of well testing
    - DST string
    - Downhole gauge carrier (incl. back up)
    - Shut in downhole valve (To be confirmed from the design)
- Fluids: for the purpose of well test (injection)
    - Injection fluid: fresh water (amount to be confirmed from design)
    - Inhibitors: to prevent scale formation due to incompatibility between fresh water and reservoir formation water
- Wellhead configuration: pressure gauge installation; shut-in valve
- Rig (surface) facility: adequate injection fluid (compatibility with formation brine); adequate waste storage capacity; cement pumping unit capacity; surface pressure or rate limitations, rig equipment pressure rating
- Data acquisition: maintain accurate and continuous records of injection rates, pressure, and temperature.

5.1.3 Well maintenance plan.

The well maintenance plan outlines long-term maintenance and integrity requirements for safe and leak-free CO_2 injection operations over lifecycle of the injector well. The well is a pressure containment vessel that must be monitored, inspected, maintained and information recorded to ensure integrity is assured. Managing well integrity is essential to economically inject CO_2 underground while preserving the environment and assuring safety to personnel.

The well maintenance plan shall follow Industry standards, local regulations and internal policies related to well integrity. This plan provides guidelines and procedures for well integrity monitoring & maintenance program in order to maintain the risk as low as reasonably practicable and identify any potential issue. Its purpose is to maintain two independent well barriers at all times, detect anomalies early, prevent CO_2-related degradation, and minimize downtime through systematic preventive maintenance and well interventions when required.

The plan will cover the lifecycle of the asset from start to end of operations.

- Pre CO_2-injection shall require inputs such as baseline logs (for cement bond, casing thickness, temperature,
- During operations: Routine monitoring of surface and subsurface values, perform intervention and workovers according to lifespan of key components and perform periodic integrity evaluation/testing of main barriers.
- P&A: planning and monitoring.

Because CO_2 has unique corrosive and thermal behaviour, the maintenance plan places particular focus on corrosion management, pressure surveillance, valve operability, and verification of barrier health.

Maintenance is divided into daily, monthly, quarterly, annual, and multi-year tasks. Activities address the wellhead, Christmas tree, annulus, subsurface safety devices, sensors, tubing/packer integrity, and surface facilities up to the injection choke.

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1. **Daily tasks**
   Main objective is to detect anomalies using real-time operating data such as tubing head pressure, annulus pressure, wellhead and downhole temperature, flow rate, and pressure-rate trends. These parameters are monitored to detect deviations from the expected operating envelope. Operators shall visually inspect the wellhead daily to ensure there are no leaks, icing, unusual noises, or changes in valve position. Any change in annulus pressure outside the approved limits is logged and investigated immediately, as annulus behaviour is one of the earliest indicators of packer, tubing, or cement health degradation.
2. **Monthly tasks**
   Monthly maintenance expands the mechanical review of the surface system. All valves on the Christmas tree are operated, lubricated, and checked for leakage or increased torque. The annulus corrosion-inhibitor program is validated to ensure chemical protection remains effective against potential CO_2 exposure. Instrumentation cables and downhole data acquisition systems are inspected for damage or signal deterioration, and pressure and temperature sensors are calibrated to maintain accuracy. It is recommended to verify CO_2 stream quality (dryness, impurities).
3. **Quarterly tasks**
   Quarterly activities verify the safety-critical systems. Emergency shutdown valves undergo partial-stroke tests, and the safety system is function-tested. Surface flowlines and wellhead assemblies are inspected for CO_2-related corrosion, erosion, and cold-temperature embrittlement.
4. **Annual tasks**
   Annual maintenance provides a higher level of assurance. A full well integrity test is performed, including pressure testing of the tubing, annulus, and surface well barriers. Pressure safety valves are recertified, and the entire safety instrumented system undergoes a full proof test. Valve servicing is completed as per OEM standards, and non-destructive examination is performed on critical metal components to detect early corrosion or thinning.
5. **Multi-year tasks** (3-5 years)
   This maintenance will require the use of an external unit such workover rig or Coil tubing depending on the scope of work to be performed. Choke trims may be removed for inspection due to erosion, and downhole logs may be run to assess tubing and casing corrosion, evaluate cement integrity, and identify micro annulus development. Downhole gauges may also be retrieved and recalibrated. If high levels of corrosion are observed, then some parts of the completion might need to be replaced. The Intervention Criteria will be established in the basis of operation but will include the following:
   - Persistent annulus pressure build up after bleed off
   - Confirmed tubing or packer leak
   - Wellhead/valve leakage that cannot be repaired online
   - Severe corrosion or erosion exceeding allowable limits
   - Downhole sensor/data failure impacting safe operations
   - Significant deviation from reservoir or well model predictions

All the above tasks shall be properly recorded and reported.

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5.1.4 Well containment plan

This plan defines how containment of injected CO_2 will be maintained during operation, temporary suspension, and abandonment. It sets the barrier strategy, materials selection, verification tests, monitoring, and LoC (Lost of Containment) response required to ensure safe long-term CO_2 storage.

The CO_2 will be injected in the Bundsandstein formation at a depth ranging from 1697 m to 1839 m with the target reservoir being the B1 from 1761 m to 1839 m. The main caprock will be the middle and upper Triassic evaporites. The main risks include reservoir over-pressurization, unplanned plume migration, leakage through nearby wells, degradation of cement or elastomers due to CO_2 exposure. These risks are mitigated by applying conservative injection pressure limit called Maximum Allowable Injection Pressure (MAIP), using CO_2-resistant materials, having two independent and always functioning well barriers, and implementing a robust monitoring program to verify conformance with reservoir models.

Containment relies on a two-barrier philosophy. The primary barrier envelope consists of CO_2-resistant injection completion (tubing, packer, SSSV) and the surface Christmas tree including master and wing valves and emergency shutdown systems. The secondary envelope includes the production liner + tieback, CO_2-resistant cement placed across the reservoir and caprock, and wellhead and casing hanger seals. All barrier elements must withstand CO_2-rich environments. Tubing, packer components, and critical metalwork are selected from corrosion-resistant alloys such as 13Cr, 25Cr, or nickel-based materials. Seals and elastomers are selected for CO_2 performance (e.g., HNBR, FKM, or metal-to-metal systems). Cement systems are engineered to resist carbonation. Annulus fluids are treated with corrosion inhibitor and oxygen scavenger, and the injected CO_2 stream must meet dryness and impurity specifications to limit corrosion risk.

Operationally, the well must stay within the defined operating envelope. This includes setting the target injection rate, the maximum allowable injection pressure at the perforations, the maximum allowable operating pressure at the tree, and temperature limits tied to CO_2 cooling behaviour. Annulus pressure limits are based on the lowest rated element. Injection is initiated via controlled ramp-up steps to observe stabilization behaviour. Real-time surveillance is maintained for tubing and annulus pressure, temperature, flow rate, differential pressure, and system alarms. The emergency shutdown shall be triggered by high bottom hole pressure, high annulus pressure, rapid pressure changes, or low temperature near the choke or tree.

Before injection, well integrity shall be verified by pressure testing all casing strings, evaluate cement quality across caprock and other critical intervals, and conducting formation integrity tests where allowed. The completion is pressure-tested above and below the packer, and the Christmas tree and surface flowlines are pressure tested and function-tested.

Monitoring, measurement, and verification shall be done to confirm that injected CO_2 remains contained and behaves as predicted in the static-dynamic model. Measurements are regularly compared against reservoir simulations; deviations trigger updates to operating limits through a management-of-change process.

Several loss-of-containment scenarios might occur such as:

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- Annular pressure buildup may indicate microannulus development or a packer leak; the response is to reduce injection rate or shut in, bleed off pressure safely, evaluate barrier elements, and remediate if necessary.
- Tubing leak requires shutdown, pressure testing, diagnostics, and potential retrieval and replacement of tubing.
- Failure of casing or wellhead seals require isolation, securing the area, and component repair or remediation.
- Exceeding fracture limits or observing accelerating pressure behaviour may signal over-pressurization, requiring immediate rate reduction or shutdown and reassessment of injection limits.

5.2 HSE technical plan.

5.2.1 Introduction

The Health, Safety, and Environmental (HSE) deliverables for a Carbon Capture and Storage (CCS) project such as the Lopin CCS injection well are defined according to the project phase. Each stage: conceptual, definition, execution, and closure require specific documentation and controls to ensure compliance with regulatory requirements, manage risks, and maintain stakeholder confidence.

Currently, the project is in the **Conceptualization Phase**, which focuses on establishing a strategic framework, identifying major hazards, and defining preliminary safety and environmental requirements. This phase is critical for setting the foundation for safe operations and environmental stewardship before moving into detailed engineering and execution

The deliverables included in this document represent the minimum HSE requirements for the conceptualization stage. They provide the foundation for safe operations and environmental stewardship throughout the lifecycle of the CCS project. These deliverables include:

- **HSE Project Plan:** Defines the overall safety and environmental strategy, policies, and objectives.
- **S&E Related Permitting Plan**: Ensures compliance with all regulatory requirements and permits (Deliverable 4.7 - Chávez *et al.,* 2025)
- **HAZID Assessment Report:** Identifies hazards early in the design phase and proposes mitigation measures.
- **Bow-tie Analysis for Major Accident Hazards:** Visual representation of barriers and controls for high-risk scenarios such as CO_2 leakage.
- **Emergency Response Plan:** Establishes procedures for managing incidents, including CO_2 leaks and well control events.
- **Environmental, Social, and Health Impact Assessment (ESHIA):** Evaluates potential impacts and defines monitoring and mitigation strategies.

In the following sections, each deliverable will be described, highlighting its purpose, scope, and relevance to the Lopin CCS project.

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5.2.2 HSE Plan

5.2.2.1 Policies, Strategy and Objectives Management

1. Project Description: The CCS pilot project in Belchite aims to demonstrate the technical and economic feasibility of CO_2 capture and storage in the Ebro Basin. It involves drilling one or two injection wells, conducting tests, and monitoring subsurface CO_2 behaviour & potential leakage.
2. S&E Policy and Principles: The project adopts a Zero Harm approach aligned with ISO 14001, ISO 45001, and EU CCS Directive 2009/31/EC. Principles include proactive risk management, regulatory compliance, stakeholder transparency, and continuous improvement.
3. Objectives and KPIs: Targets include zero lost-time incidents, full compliance with permits, prevention of CO_2 leakage (<0.1%), and active community engagement.

5.2.2.2 Organization, Resources and Capability Management

1. Organization Charts: Define roles such as Project Manager, HSE Lead, Wellsite Supervisor, Environmental Specialist, and Community Liaison.
2. RACI Chart: Assign responsibilities for risk assessments, emergency response, monitoring, and reporting.
3. Training Requirements: All personnel will receive CCS-specific inductions covering CO_2 hazards, emergency drills, and confined space safety.
4. Workforce Competence Certification: Includes certifications for handling pressurized gases, first aid, and well control.
5. Communications Management: Establish protocols for internal coordination and external reporting to authorities and stakeholders. (Deliverable 7.2)

5.2.2.3 S&E Stakeholder Management

1. Stakeholders Register: Includes MITERD, Government of Aragón, local municipalities, NGOs, and academic institutions.
2. Stakeholder Management Plan: Transparent communication through newsletters, public meetings, and digital platforms.
3. Local Communities Register & Engagement Plan: Engagement via workshops in Belchite and Zaragoza to address concerns and explain CCS benefits.
4. HSE Legal Requirements: Compliance with Spanish Law 34/2007, RD 975/2009, and EU CCS Directive.

5.2.2.4 Contractor and Supplier Management

1. Services to be Contracted: Drilling, CO_2 transport, geophysical monitoring, laboratory analysis.
2. S&E Requirements for Contracts: Mandatory HSE clauses, audits, and KPIs.
3. Contractors Qualification: Verification of certifications and HSE performance history.
4. Bridging Documents: Integration of contractor HSE systems with project standards.
5. Performance Monitoring: Monthly HSE reports and compliance checks.

5.2.2.5 Risk and Impact Management

1. Hazard and Risk Assessments: Includes HAZID, HAZOP, Bowtie for CO_2 release, and ESHIA.
2. CCS-Specific Risks: High-pressure CO_2 handling, well integrity failure, induced seismicity, corrosion, and environmental contamination.
3. Emergency Management: Detailed response plan for CO_2 leaks, evacuation routes, and medical support.
4. Site Restoration Management: Post-project land rehabilitation and monitoring.

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5.2.2.6 Asset Design and Integrity

1. SECEs Management: Identification and maintenance of safety-critical elements such as valves, sensors, and barriers.
2. Integrity Assurance: Regular inspections, pressure testing, and corrosion monitoring to prevent CO_2 leaks.

5.2.2.7 HSE Planning Management

1. Hazard Management Action Plan: Defines mitigation measures for identified risks.
2. ESHIA Management Plan: Evaluates environmental, social, and health impacts.
3. Waste Management Plan: Covers drilling fluids, cuttings, and contaminated soil.
4. Monitoring Program: Includes CO_2 sensors, groundwater sampling, and seismic monitoring.
5. Emergency Response Plan: Procedures for CO_2 release scenarios and evacuation.
6. HSE Permits Plan: Tracks regulatory approvals and compliance milestones.

5.2.2.8 Execution and Control of Activities

1. Permit to Work System: Controls high-risk tasks such as drilling and injection.
2. Management of Change: Ensures safe implementation of design or operational changes.
3. Lifting and Hoisting: Procedures for safe handling heavy equipment.
4. Occupational Safety: Measures to prevent CO_2 exposure and ergonomic risks.
5. Transportation Management: Safety protocols for land and air transport of CO_2 and equipment.
6. Safety Observations: Continuous monitoring and reporting of unsafe conditions.

5.2.2.9 Monitoring, Reporting, Improvement and Learning Management

1. GHG Emissions Reporting: Ensures compliance with environmental standards.
2. Emissions Monitoring: Tracks CO_2 levels during well testing and injection.
3. KPI Tracking: Includes LTIF, CO_2 leak incidents, and permit compliance.
4. Continuous Improvement: Lessons learned and corrective actions implemented promptly.

5.2.2.10 Verification and Audit Management

1. HSE Inspections: Daily during drilling and monthly during monitoring.
2. HSE Audits: Internal and external audits involving authorities, NGOs, and community representatives.
3. Compliance Assurance: Findings feed into corrective actions and improvement plans.

5.3 S&E related permitting plan

This section summarizes the permitting requirements for drilling injection wells during the exploitation phase of the Belchite CCS project. It provides the Project Manager with a clear roadmap to manage regulatory authorizations, ensuring compliance and alignment with the overall project schedule.

As part of the Pilot Strategy, AECOM prepared a detailed Permit Road Map for the Belchite CCS project in March 2025 (Deliverable 4.7 – Chávez *et al.,* 2025). That report can be consulted for comprehensive information. Below is a concise summary of the key permits required for the injection wells planned during the exploitation phase.

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5.3.1 Key Permits and Authorizations

5.3.1.1 Storage Concession (Framework Permit)

- Authority: MITECO (Ministry for Ecological Transition and Demographic Challenge).
- Legal Basis: Law 40/2010 on Geological Storage of CO_2.
- Scope: Grants the right to store CO_2 and includes injection wells within the approved storage project.
- Requirements:
  - Site characterization and safety assessment.
  - Operation plan (injection rates, pressures, monitoring plan).
  - Environmental Impact Study (ordinary procedure).
  - Financial guarantee for closure and post-closure obligations.

Estimated Processing Time: Up to 12 months (excluding environmental assessment delays).

5.3.1.2 Environmental Impact Assessment (EIA – Ordinary Procedure)

- Authority: MITECO – Directorate for Environmental Quality and Assessment.
- Legal Basis: Law 21/2013 on Environmental Assessment.
- Scope: Mandatory for storage sites under Law 40/2010; includes injection wells or seismic acquisition.
- Requirements:
  - Full EIA report covering construction, operation, and closure phases.
  - Public consultation and Natura 2000 compatibility analysis.

Estimated Processing Time: 12–16 months (including consultations).

5.3.1.3 Land Occupation and Urban Planning Permits

- Authority: Local municipalities (e.g., Belchite, Fuente de Ebro).
- Legal Basis: Urban Planning Law of Aragon (Legislative Decree 1/2014).
- Requirements:
  - Municipal planning license.
  - Special use authorization for non-developable land (requires Provincial Urban Planning Council report).
- Dependencies: Linked to EIA and storage concession approval.

5.3.1.4 Additional Considerations

- Cultural Heritage Authorization: Required if works affect Assets of Cultural Interest (BIC).
- Public Utility Declaration: Granted with storage concession; enables forced expropriation if needed.
- Communication of Start of Works: Recommended to maintain stakeholder engagement.

5.4 HAZID Assessment Report

5.4.1 Objectives

The objective of this HAZID (Hazard Identification) is to identify, in a preliminary and conceptual manner, the main hazards associated with the development of the pilot project for geological CO_2 storage in the surroundings of Belchite (Zaragoza). This analysis establishes the basis for defining

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safety, environmental and social requirements that must be expanded in subsequent phases (PREFEED, FEED and detailed design).

The risks included in this section are supported by the project's Risk Register, which contains 39 threats and 33 opportunities distributed across PESTLE categories (Political, Economic, Social, Technological, Legal, Environmental and Safety).

5.4.2 Methodology

The assessment has been carried out through:

- Review of the project's conceptual Risk Register (22/09/2025). Summarized in Deliverable 5.4, Work package 5.4
- Risk classification according to the PESTLE framework.
- Application of qualitative probability and impact criteria appropriate to the conceptual stage.
- Integration of historical geological and operational information from wells previously drilled in the area (Monegrillo-1, Ballobar-1, Candasnos-1, Ebro-1, Lopín-1, among others).
- A multidisciplinary approach considering process safety, well integrity, environment, regulatory aspects and social perception.

Given that the project does not yet have a final design or complete subsurface characterization data, this HAZID for all project phases shall be interpreted as an early strategic guide.

5.4.3 Local context of the Belchite Site

The selected area, located southeast of Belchite, is characterized by:

- Low population density and predominant agricultural land use.
- Presence of legacy wells drilled between 1958 and 1981, some within the area of influence of the pilot well.
- A low-seismicity context but with deep structures typical of the Ebro Basin.
- High social sensitivity to changes in land use and water resource availability.
- Presence of steppe-type environmental values and cultural heritage (Belchite Viejo).

This context shapes the project's risk profile.

5.4.4 Main hazards identified.

Risk identification using the Risk Register methodology (property of Repsol) has also been applied on the Paris Basin case. Risk categories and probability/impact thresholds are described in Subchapter 4.4.1 above. For Ebro Basin, Risk Register matrices, before and after response, are shown in Figure 25 & Figure 26. Considered risks are listed in Table 12.

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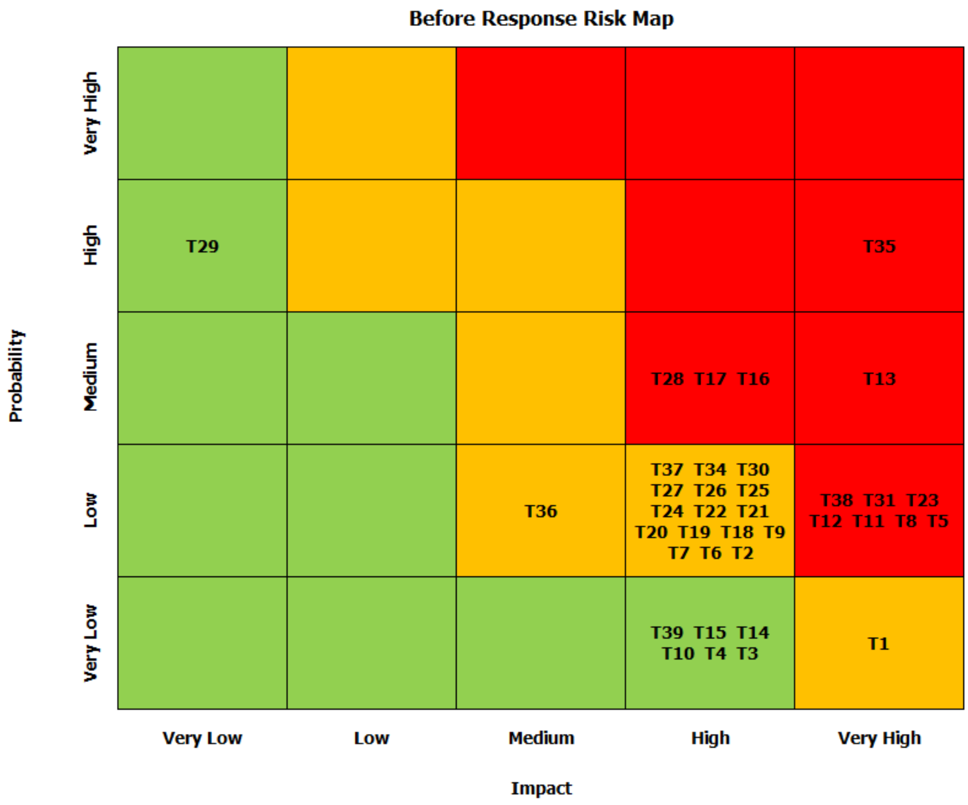

Figure 25 Risk Register matrix before response

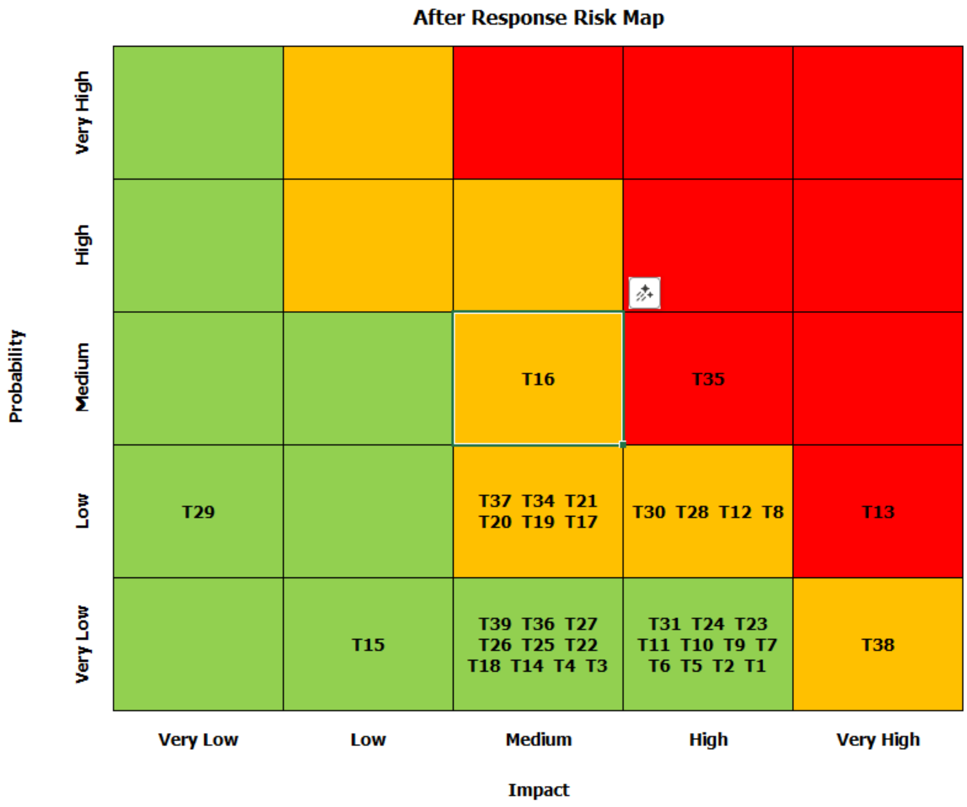

Figure 26 Risk Register matrix after response

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Risks included in the Risk Map	
T1	**Vertical leakage through caprock (sealing deficiency)**
T2	Vertical leakage along faults or fractures
T3	Structural spill
T4	Lateral leakage
T5	Leakage from operating well
T6	Leakage from legacy abandoned well
T7	Migration of formation brine outside expected boundaries
T8	Induced seismicity
T9	Disruption by a later activity
T10	Changes in groundwater flow, within the reservoir or in other layers of the storage complex
T11	Loss of Injectivity
T12	Lower than expected capacity
T13	Unexpected compartmentalization
T14	Accidental Over-fill
T15	Uplift or subsidence of ground
T16	Delays or inability to obtain key permits
T17	Lack of financial incentives or changes in CO_2 pricing
T18	Unexpected construction or operational cost changes
T19	Uncertainty in CO_2 supply sources
T20	Public opposition or lack of social acceptance
T21	Erosion of public trust in developers and authorities
T22	Lack of maintenance or emergency procedures
T23	Corrosion or material issues in pipelines or wells
T24	Unforeseen CO2 impacts
T25	Conflicts with other subsurface or surface land uses
T26	Unexpected variations in CO_2 composition
T27	Mismatched performance between system components (capture, transport, storage)
T28	Lack of internal support within the companies due to CCS competing with other business lines
T29	Competitor securing acreage before Pilot (first-mover disadvantage)
T30	Lack of sufficient power distribution infrastructure for hub operations
T31	Dense-phase CO_2 pipeline rupture near populated areas (safety and design implications)
T32	NZIA accelerated adoption by Spain authorities
T33	Access to subsidies
T34	Distributive and procedural related conflicts
T35	Unstable political support and regulatory uncertainty
T36	Intergenerational/ Legacy concerns
T37	Social fragmentation/ polarization
T38	Fracturing of the caprock induced by injection
T39	Natural seismicity

Table 12 Considered risks

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A. Environmental and Safety Risks (EN)

1. **CO_2 leakage through legacy wells**
    - Increased relevance due to the existence of up to 10 historical wells drilled in the immediate surroundings of the project (1958–1981).
    - Implication: need for integrity audits and abandonment verification.
2. **CO_2 migration into shallow aquifers**
    - Presence of Quaternary aquifers used for irrigation and livestock.
    - Relevant risk due to potential environmental and social impacts.
3. **Induced seismicity**
    - Although the area has low natural seismicity, the possibility is considered in a generic form.
    - A perceptible microseismic event could trigger local concern.
4. **CO_2 accumulation in gullies or micro-depressions**
    - Local topography with ravines and shallow depressions susceptible to accumulation of dense gas.
5. **Failure of monitoring equipment or sensors**
    - Risk associated with failure of maintenance or critical monitoring systems.

B. Technological Risks (T)

1. **Loss of injectivity or effective capacity lower than estimated**
    - Reservoir heterogeneity in the Ebro Basin suggests risk of loss of permeable porosity or compartmentalization.
2. **Variability in the composition of transported CO_2**
    - Risks associated with corrosion or deposition due to impurities in the CO_2 stream.
3. **Operational risks related to CO_2 transport**
    - Depending on the transport method (truck or pipeline), scenarios may include pipeline rupture or transportation incidents.
4. **Failure or misalignment across capture–transport–storage**
    - Asynchrony between the development of CCS chain components.

C. Regulatory and Legal Risks (R/L)

1. **Significant delays in key permits**
    - Regulatory complexity and need for a full EIA, storage concession and municipal authorizations.

2. **Landuse conflicts**
    - Coexistence with agricultural uses, protected steppe areas, or cultural heritage.
3. **Traceability and post-closure liability requirements**
    - Risks associated with uncertainty regarding long-term responsibility.

D. Social Risks (S)

1. **Public opposition due to risk perception**
    - Concerns about leakage, aquifer impacts, and seismicity.
    - Belchite has historical precedents of resistance to energy infrastructures.
2. **Reputational risks due to proximity to cultural heritage**
    - Belchite Viejo is a symbolic landmark with significant tourism value.
3. **Intergenerational concerns**
    - Uncertainty regarding long-term storage integrity.

E. Economic Risks (E)

1. **Dependence on CO_2 price and public incentives**
    - Economic volatility and lack of incentives may compromise viability.
2. **Limited regional supply chain**
    - Potential increase in CAPEX/OPEX due to logistics and the need for external contractors and equipment.

5.4.5 Identified Opportunities

The Risk Register also identifies several opportunities related to:

- Regulatory acceleration (NZIA) and institutional support.
- Access to European and national funding, particularly for pilot decarbonisation projects.
- Potential positive social acceptance if local benefits and emissions reduction are effectively communicated.
- Development of regional technical capabilities linked to CCS technologies.

These opportunities can mitigate political, social and financial risks if managed strategically.

5.4.6 Maturity Level of the Analysis

This HAZID is conceptual in nature. It will require updating once the following are available:

- Final geological model and geophysical logging results.
- Preliminary design of the pilot well (PREFEED).
- Decision on the CO_2 transport method.
- Baseline environmental studies (geological, hydrogeological and biodiversity).
- Preliminary MMV plan.

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5.4.7 Recommendations for Subsequent Phases

- Conduct a comprehensive assessment of legacy wells, including abandonment verification and communication risk.
- Develop a full Bow Tie for prioritized main hazards (CO_2 release, induced seismicity, aquifer impact).
- Integrate a preliminary MMV programme, including passive seismic and aquifer monitoring.
- Perform a HAZOP prior to completing FEED.
- Design an early community-engagement strategy in Belchite and neighbouring municipalities.
- Coordinate a detailed regulatory roadmap with MITERD and the Government of Aragón.

5.4.8 Overall HAZID Conclusion

The Belchite area presents a set of risks characteristic of CCS projects, reinforced by the presence of legacy wells, sensitive steppe ecosystems, locally valuable water resources and a social context in which public acceptance is crucial. Nevertheless, these risks are manageable through good design practices, robust monitoring and transparent communication, and are balanced by significant regulatory and innovation opportunities for a pilot-scale project in Spain.

5.5 Emergency response plan

5.5.1 Purpose of ERP

The purpose of this Emergency Response Plan (ERP) is to define the structure, roles, responsibilities and emergency management procedures for the geological CO_2 storage pilot project in Belchite (Zaragoza), during the drilling, testing and initial injection phase.

The ERP establishes:

- The response levels and the ICS organization applicable to Repsol projects in Spain.
- The notification, communication and escalation mechanisms between contractor (FRP/FRT), Repsol Exploration/LCS (IMT) and Repsol Corporativo (CMT).
- The main emergency scenarios derived from the HAZID and the project's Risk Register.
- The specific emergency plans that must be developed in subsequent engineering phases.

5.5.2 ICS Emergency Response Structure for the CCS Belchite Project

The response organization follows the Incident Command System (ICS), adapted to an exploratory project under Spanish regulation.

1. Field Response Plan / Field Response Team (FRP/FRT)

Responsible: CCS Well Drilling Contractor

Nature: Tactical and immediate response, 24/7.

Functions: Control the incident on site.

- Activate your own emergency procedures (blowout, fire, CO_2 leak, accident).
- Perform evacuation, first aid, and initial containment.
- Communicate to the On-Scene Commander (OSC) and Repsol.

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- In Spain, the contractor must have its own Self-Protection Plan (RD 393/2007).

2. IMT – Incident Management Team (Repsol Exploration / Low Carbon Solutions)

Responsible: Repsol, through the designated Incident Commander (IC).
Functions:

- Strategic direction of the response.
- Coordination with Spanish authorities:
    - 112 Aragon
    - Civil Guard
    - Provincial Council Firefighters
    - Civil Protection
    - INAGA/MITECO if applicable
- Logistics management, external communication, security, environment, HR and technical support.
- Assessment of climbing potential.
- Preparation of the Incident Action Plan (IAP).
- Incident Commander (IC) – Repsol

3. CMT – Crisis Management Team (Repsol Corporate)

Activation only if the emergency reaches impact: serious, multisite, media, significant environmental or with multiple victims.

CMT Functions:

- Global Reputational Management
- Corporate strategic decisions
- Communication with national and international stakeholders
- Specialized support (technical, legal, geomechanical, social)

5.5.3 Notification Flow and Escalation During an Emergency

1. The emergency starts in the field – FRT

Whoever detects the event → triggers internal contractor alarms

2. The OSC notifies Repsol (24/7)

- The OSC immediately informs:
- Repsol's Wellsite Representative (WSR), and
- Duty Manager / Repsol Guard.

3. Repsol evaluates whether it activates IMT

IMT is activated when:

- the FRT does not control the situation,

- there is an impact outside the site,
- there may be an impact on third parties,
- The authorities demand it.

4. The IMT notifies the CMT if there is a potential for crisis.

5.5.4 Emergency Scenarios to be covered (derived from the HAZID of the CCS Belchite)

1. Traffic accident (construction and CO_2 transport vehicles)

- Collision of vehicles on rural roads.
- Overturning of a tanker truck transporting CO_2 (if applicable).

2. General evacuation of the site

- Triggered by fire, CO_2 leakage, perceived seismicity, or others.
- It must include muster points, evacuation routes and signage.

3. Blowout or Well Control Incident

- Fluid or CO_2 leakage during drilling or testing.
- BOP activation, well shutdown, and specialized deployment.

4. Loss of Surface CO_2 Containment (Release)

- Rupture of line, flange, valve or equipment.
- Plume of CO_2 accumulated in troughs or depressions.

5. CO_2 leakage from nearby legacy well

- Activation of monitoring due to anomaly or leakage.
- Serious scenario due to social and environmental sensitivity.

6. Detected or perceived induced seismicity

- Activation of the Traffic Light System (TLS).
- Immediate stop of operations if it stops.

7. Fire or explosion

- Hot work.
- Electrical failure.
- Fire in drilling machinery.

8. Medical Emergency

- Personnel injured or sick on site.
- Coordination with 061 Aragón.

9. Severe weather conditions

- Extreme wind, storms, extreme heat.
- Suspension of operations and orderly evacuation.

10. Significant failure in critical monitoring systems (MMVs)

- Loss of ability to detect leaks.
- Immediate escalation to IMT.

5.5.5 Specific Emergency Plans that are estimated to be prepared for this project.

1. Medical Response Plan (MEDEVAC)
2. Action Plan for Traffic Accidents
3. General Site Evacuation Plan
4. Blowout / Loss of Well Control Emergency Plan
5. CO_2 Leakage Response Plan (surface or legacy well)
6. Fire or Explosion Response Plan
7. Induced Seismicity (TLS) Response Plan
8. Critical Systems Failure (MMV) Contingency Plan
9. Internal and external communication plan in emergencies
10. Coordination plan with Spanish authorities (112, Firefighters, Civil Guard, Civil Protection).

Additional plans recommended in CCS (based on the best international practices):

1. Access control and CO_2 containment plan
2. Post-event environmental monitoring plan
3. Operational Continuity Plan (BCP) for the pilot phase
4. Specific plan for interaction with legacy wells

5.6 MMV plan.

5.6.1 Introduction

This report documents the Monitoring, Measurement and Verification (MMV) plan designed for a geological CO_2 storage project in the Ebro Basin, targeting Triassic sandstones (Buntsandstein) at approximately 1,800 m depth. The plan is risk-based and aligned with ISO 27914 and the EU CCS Directive 2009/31/EC and associated guidance. It is structured to demonstrate: (i) containment (no migration beyond the storage complex), (ii) conformance (plume and pressure evolution consistent with the dynamic model), and (iii) operational performance (safe injection within P/T/Q limits and well integrity), providing auditable evidence to regulators and stakeholders throughout the project lifecycle, through closure and beyond.

5.6.2 MMV objectives and risk-based strategy

The MMV Plan Objectives are:

- Demonstrate containment of CO_2 within the authorized storage complex, with auditable evidence for regulators.
- Verify conformance: show that plume and pressure evolve as predicted by the dynamic model; update the model with monitoring data.
- Ensure operational performance and well integrity: keep injection within P/T/Q limits, apply defined thresholds and responses (e.g., seismic TLS, pressure, InSAR, groundwater, soil-gas) for adaptive risk management.

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- Align with EU standards (ISO 27914; Directive 2009/31/EC), integrating multiple lines of evidence (e.g., VSP/DAS, InSAR, hydrochemistry, CO_2-flux) across baseline, injection, closure, and post-closure.

The program applies layered lines of evidence across wellbore sensors, borehole/surface geophysics (DAS/VSP, Gravimetry, EM surveys), surface deformation (InSAR), groundwater hydrochemistry, soil-gas and CO_2-flux surveys, and contingency tracers. Elements of concern include injector and legacy-well integrity, caprock/fault transmissibility, shallow aquifers (Jurassic monitoring wells), induced microseismicity, surface deformation, and diffuse surface emissions.

In the development of this monitoring plan, other CO_2 injection projects that have already been implemented were considered, such as Decatur (USA), In Salah (Algeria), and Quest and Aquistore (Canada).

5.6.3 Thresholds and response actions

Operational and monitoring responses are triggered by thresholds to support adaptive risk management.

- Reservoir pressure: Sustained +15% versus forecast → reduce injection rates, redistribute between injectors, and re-simulate.
- Microseismicity (DAS/local array): Traffic-light system: ML < 1.5 near seal/fault → Green; ML ≥ 1.5 near seal/fault → Yellow (rate reduction; contingent VSP); ML ≥ 2 → Red (shut-in + diagnostics).
- CO_2 gas flux at wellhead or surroundings: Investigate and apply operational/corrective measures per procedures.
- Surface deformation (InSAR): Trend > 5 mm/yr uplift → reduce rates and revisit pressure management.
- Groundwater: Consistent pH/alkalinity/EC shifts → densify sampling + isotopic lines of evidence.
- Soil gas / CO_2 flux: Excursions above seasonal P95 → dense grid + tracer pulse (contingency) to resolve pathways.
- Well integrity: Annulus anomalies or CBL/USIT issues → remedial workover and verification logging.

5.6.4 Evaluated cases

Four development and monitoring configurations were evaluated, varying the number of injectors and the combination of geophysical tools (VSP/DAS/Gravimetry/EM versus surface 3D/4D seismic), to balance conformance sensitivity, risk coverage, and full lifecycle cost.

5.6.4.1 Scenario overview and costs (Table 13)

Scenario	Technical description	Total cost (EUR)	Notes
Scenario 1	1 injector; 7.5 Mt over 30 years (~0.25 Mtpa); no surface seismic; VSP + Grav./EM.	12,588,052	Core conformance from VSP + DAS + InSAR plus groundwater/surface assurance. Gravimetry and EM to be tested; retain the most effective.
Scenario 2 (BASE CASE)	2 injectors; 15 Mt over 30 years (~0.5 Mtpa); no surface seismic; VSP + Grav./EM.	18,707,604	Same core program scaled to two shallow wells and per-injector VSP/DAS; improved

			conformance sensitivity. Gravimetry and EM to be tested; retain the most effective.
Scenario 3	2 injectors; 15 Mt over 30 years (~0.5 Mtpa); no surface seismic; no operational VSP (baseline only); Grav./EM.	14,707,604	Same core program with per-injector DAS; VSP only in baseline (no operational repeats).
Scenario 4	2 injectors; 15 Mt over 30 years (~0.5 Mtpa) + 4D seismic every 4 years during injection and every 7 years during closure/post-closure; no VSP; no Grav./EM.	61,227,604	4D in baseline + injection + closure + post-closure; no additional techniques (no VSP, no Grav/EM).

Table 13 Main MMV scenarios for Lopin injection site

5.6.4.2 Emphasis on the base case (Scenario 2)

The base case (two injectors, 15 Mt over 30 years, ~0.5 Mtpa) is the reference for detailed MMV design. It maintains a robust monitoring program without surface seismic, focusing conformance sensitivity on borehole-first tools (repeated VSP and continuous DAS) and surface deformation (InSAR), complemented by groundwater and near-surface assurance lines. A multi-physics approach (gravimetry and electromagnetic) is included in early years to test detectability and retain the most effective technique for the remainder of the project. VSP is assumed to be a valid technique, supported by a previous feasibility study.

5.6.4.3 Other scenarios (Scenario 1, 3, 4)

Scenario 1 scales the same philosophy to one injector and lower total injected mass. Scenario 3 explores a cost reduction by removing operational VSP (baseline only) while retaining DAS and Grav/EM. Scenario 4 replaces the borehole-first and multi-physics toolkit with an intensive surface 4D seismic program across all lifecycle phases, significantly increasing total cost.

5.6.5 Selected technologies and unit costs.

Table 14 Techniques and unit costsTable 14 summarizes the unit costs (CAPEX, O&M, or per-campaign) for the MMV programme.

Technology / activity	Unit cost
Jurassic monitoring well (~900 m)	€150,000 CAPEX per well; pH/EC €8,000 CAPEX per well; €1,500/yr O&M per well.
Water geochemistry	€1,056 per campaign (1 baseline; 3/yr during injection & closure; 1 annual during post-closure).
Soil gas & surface CO_2 flux	€15,000 per campaign (1 baseline; 3/yr during injection; 1/yr in closure; every 3 years in post-closure).
CO_2 stream (composition/quality)	€5,500 per campaign (1 baseline; 3/yr during injection & closure).
P/T/Q + annulus monitoring	€150,000 CAPEX per injector; €10,000/yr O&M per injector (during injection).
DAS	€700,000 CAPEX per injector; €25,000/yr O&M per injector (during injection); stand-by in closure/post-closure. Mobilization/demobilization not included.

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CBL/USIT (well integrity)	€40,000 per campaign per injector (baseline + final at end of closure).
2D VSP (walkaway; subject to feasibility study)	€200,000 per campaign per injector (baseline; annually Y1–Y3; Y6; Y9; every 5 years thereafter + final at Y30).
Natural seismicity baseline	€150,000 (network + 1 year recording).
InSAR	€100,000/yr (baseline + injection + closure).
CO_2 detectors (wellhead/cellar)	€10,000 CAPEX per injector; €1,000/yr O&M per injector (during injection).
Tracer (contingency)	€120,000 per pulse.
3D/4D seismic (per acquisition)	€2.12M (1 injector); €4.26M (2 injectors).
Gravimetric survey / EM survey	0.3 MUSD per survey and technique. Apply both methods in baseline and additional repeats during injection; after testing performance, retain only the most effective technique.

Table 14 Techniques and unit costs

5.6.6 Base case description (Scenario 2)

This section describes the base case MMV program by lifecycle phase: baseline, injection, closure and post-closure, including the economic breakdown by phase.

5.6.6.1 Baseline program (Year 0)

The baseline phase establishes pre-injection references needed to detect injection-induced changes and to bound natural variability (seismicity, deformation, groundwater chemistry, soil gas).

- 2D walkaway VSP per injector (baseline).
- Microseismicity: local array (≥5 geophones) with baseline recording and DAS coupling.
- InSAR: baseline processing and reference grid.
- Baseline gravimetry + electromagnetic surveys.
- Injectors: install P/T/Q + annulus sensors (CAPEX) and DAS (CAPEX).
- Well integrity: baseline CBL/USIT per injector.
- CO_2 detectors at wellhead/cellar (CAPEX).
- CO_2 stream: baseline composition analysis.
- Jurassic aquifer monitoring wells (~900 m): 2 shallow wells for the two-injector base case.
- Install pH/EC probe + logger + telemetry (CAPEX) in each shallow well.
- Baseline hydrochemistry (one campaign per shallow well).
- Soil gas & surface CO_2 flux: baseline grid to establish background and seasonal bounds.

5.6.6.2 Injection monitoring (Years 1–30)

During injection, continuous operational monitoring is complemented by repeated geophysical and geochemical surveys. Data are integrated through annual history matching and risk-register refresh.

- Continuous injector monitoring: P/T/Q + annulus with operational alarms (±10–15% vs expected).
- DAS O&M during injection: acoustic/strain for microseismicity, flow profiling, and pressure-front tracking.

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- CO_2 detectors O&M at wellhead/cellar.
- Gravimetry/EM: apply both techniques in Years 4 and 8; then select the best-performing technique and repeat every 4 years during injection; apply the preferred technique every 6 years in later periods.
- 2D walkaway VSP per injector in Years 1, 2, 3, 6, 9, 14, 19, 24, 29 and final at Year 30.
- Annual history matching (pressures, VSP, DAS; 4D if present) and risk-register refresh.
- InSAR service active (100 k€/yr): quarterly processing in Years 1–3 and semi-annual thereafter (per original specification).
- Water wells: continuous pH/EC O&M.
- Hydrochemistry in water wells: quarterly (Years 1–2), semi-annual (Years 3–5), annual (Years 6–30).
- Soil gas & CO_2 flux: every 3 years during injection.
- CO_2 stream composition: every 3 years during injection.

5.6.6.3 Closure (Years 31–32)

Closure consolidates evidence of containment and stabilization and culminates with final well integrity verification.

- InSAR: annual.
- Water wells: continuous pH/EC O&M.
- Hydrochemistry: 3 campaigns per year.
- Soil gas & CO_2 flux: 1 verification campaign per year.
- CBL/USIT: final campaign per injector at end of closure (Year 32).
- DAS: stand-by (no O&M).

5.6.6.4 Post-closure / post-injection monitoring (Years 33–52)

Post-closure monitoring is risk-focused and simplified while preserving key assurance lines for the long term.

- Water wells: annual hydrochemistry + continuous pH/EC O&M.
- Soil gas & CO_2 flux: one verification campaign every 3 years.
- DAS: stand-by (no O&M).
- No InSAR; no CO_2 stream sampling during post-closure.
- Electromagnetic OR gravimetric survey every 6 years.

5.6.7 Economics by phase

Table 15 summarizes the phase cost breakdown for all scenarios, supporting comparison of lifecycle cost drivers.

Phase	Scenario 1	Scenario 2 (Base)	Scenario 3	Scenario 4
Baseline (EUR)	1,869,556	3,268,612	3,268,612	6,528,612
Injection – 30 years (EUR)	9,665,040	13,985,080	9,985,080	37,105,080
Closure – 2 years (EUR)	312,336	361,672	361,672	4,621,672

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Post-closure – 20 years (EUR)	741,120	1,092,240	1,092,240	12,972,240
Grand Total (EUR)	12,588,052	18,707,604	14,707,604	61,227,604

Table 15. Phase cost breakdown for all scenarios

5.7 Comparison with Decatur, Aquistore, In Salah and Quest onshore injection projects

This section benchmarks the Ebro base case against selected onshore reference projects to highlight similarities, differences and transferable lessons for MMV design (Table 16).

Decatur (Illinois Basin–Decatur Project), Aquistore, In Salah (Krechba), and Quest were selected as onshore reference projects because they have well-documented, publicly available MMV programs and represent complementary monitoring paradigms that map directly to the Ebro design space: (i) Decatur as a borehole-first program emphasizing time-lapse VSP and microseismicity; (ii) Aquistore as a seismic-centric program with a permanent surface array complemented by DAS/VSP and environmental assurance; (iii) In Salah as an InSAR-led deformation and geomechanics benchmark; and (iv) Quest as a regulator-facing, risk-based MMV program where DAS-VSP with behind-casing fiber enables frequent repeat surveys without interrupting injection.

Aspect	Ebro – Base case (2 injectors)	In Salah (Algeria)	Decatur (USA)	Aquistore (Canada)	Quest (Canada)
Core geophysics for conformance	Repeated 2D walkaway VSP per injector (Y0; Y1,2,3,6,9,14,19,24,29,30) + DAS. Gravimetry & EM: both at Y0, Y4, Y8; then preferred technique every 4 years (injection) and every 6 years (closure/post-closure). No surface 4D.	Repeated 3D/4D seismic; microseismic (pilot); integrated with InSAR-derived pressure/deformation models.	Time-lapse VSP/4D-VSP as primary; strong microseismic (surface + downhole).	Repeated 2D/3D + permanent surface array (~630–650 shallow geophones) + DAS-VSP; continuous microseismic.	Risk-based MMV with DAS-VSP (behind casing) as main time-lapse tool; continuous downhole microseismic.
Surface deformation	InSAR annually during baseline, injection and closure.	InSAR central (mm-scale uplift/subsidence; constrains pressure field).	Reported, but not primary axis.	InSAR + GPS + tiltmeters alongside seismic arrays.	Tracked within regulator-approved, risk-based framework.
Near-surface / leakage assurance	Groundwater wells: hydrochemistry + continuous pH/EC; periodic soil gas & CO_2 flux; CO_2 detectors at wellhead/cellar.	Shallow aquifer wells, soil gas, tracers and geochemistry.	Comprehensive environmental program (deep/shallow/surface) + microseismic networks.	Groundwater + soil gas, isotopes; downhole fluid-recovery system.	Near-surface domains covered in risk-based MMV (containment & conformance).
Well / operational monitoring	P/T/Q + annulus; DAS; CBL/USIT at baseline and end-closure.	Downhole logs, fluid sampling, core and geomechanics.	P/T and repeated logging; active–passive seismic workflows.	DTS/DAS lines; repeated logging.	DTS/DAS behind casing; VSP without interrupting injection.
EM / gravity	Yes with explicit cadence and selection after performance testing.	Not headline tools in key sources.	Not prominent (VSP/microseismic dominate).	Yes, used alongside seismic.	Not central in public material

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	(focus on DAS-VSP).

Table 16 Comparison of most popular onshore CCS projects

5.7.1 Assumptions and limitations

The following assumptions and limitations clarify the context, applicability and boundaries of this report.

5.7.2 Key assumptions

- The project target is Triassic Buntsandstein sandstones at ~1,800 m depth within the Ebro Basin.
- The MMV plan is designed as risk-based and aligned with ISO 27914 and the EU CCS Directive 2009/31/EC.
- Base case adopts no surface 3D/4D seismic; conformance imaging relies on borehole-first VSP/DAS plus InSAR and multi-physics (Grav/EM).
- 2D walkaway VSP is assumed feasible and sufficiently sensitive, subject to a dedicated feasibility study.
- Gravimetry and EM are both acquired initially to test detectability; the best-performing technique is retained for subsequent repeats.
- InSAR provides sufficient coherence to detect mm-scale deformation trends relevant to pressure management.
- Operational thresholds and response actions (pressure, microseismic TLS, InSAR trend, geochemistry anomalies) are implementable within the operating procedures.
- Unit costs and phase costs are used as provided in the source presentation; where USD is used (Grav/EM), no exchange-rate normalization is applied.

5.7.3 Limitations

- Site-specific detectability (VSP, Gravimetry, EM, InSAR) depends on local geology, noise conditions, surface access and coupling; results may require updating the monitoring cadence and technique selection.
- Mobilization/demobilization for DAS is not included in the stated unit costs; additional logistical costs may apply.
- The report is constrained to the information available in the source presentation; detailed well designs, procurement specifications, permitting constraints, and integration with the full dynamic/geomechanical model are outside scope.
- The presented monitoring frequencies are pre-agreed planning cadences; a fully adaptive program may adjust frequencies based on risk register updates and model-data misfits.
- Microseismic magnitude thresholds and proximity criteria require calibration to the local seismic monitoring network and uncertainty assessment.
- Post-closure scope intentionally reduces monitoring domains (e.g., no InSAR and no CO_2 stream sampling); regulators may request modifications depending on performance evidence and local requirements.

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5.7.4 Glossary

Term	Definition
MMV	Monitoring, Measurement and Verification: activities to ensure safe and reliable operation and to verify performance by comparing observed and expected behavior (conformance) while supporting containment assurance.
Containment	Evidence that CO_2 remains within the storage complex (reservoir + seal + relevant overburden).
Conformance	Evidence that the CO_2 plume and pressure evolution match model predictions; typically supported by history matching and model updates.
Performance	Operational integrity and safe injection performance (e.g., within permitted pressure/temperature/flow limits and well integrity criteria).
Storage complex	The subsurface volume considered for safe storage: injection reservoir, caprock/seal and overburden units of concern.
Baseline	Pre-injection reference measurements used to detect changes induced by injection and to quantify natural variability.
Closure	Post-injection period to demonstrate stabilization and finalize evidence for transfer/acceptance processes.
Post-closure (post-injection)	Long-term surveillance period after closure, typically simplified and risk-focused.
EoC (Elements of Concern)	Key risk elements such as well integrity, seal/fault transmissibility, shallow aquifers, induced seismicity, surface deformation and diffuse surface emissions.
P/T/Q	Pressure/Temperature/Flow rate monitoring at the injector wellhead/downhole.
Annulus monitoring	Monitoring pressure/conditions in the well annulus to detect integrity issues.
DAS	Distributed Acoustic Sensing: fiber-optic sensing method that turns a fiber into a dense acoustic/strain measurement array along a well.
VSP	Vertical Seismic Profiling: borehole seismic method; here repeated 2D walkaway VSP is used as a conformance-imaging tool.

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Walkaway VSP	A VSP geometry with sources progressively offset from the well, improving imaging away from the borehole.
InSAR	Interferometric Synthetic Aperture Radar: satellite-based measurement of ground deformation at millimeter scale.
Microseismicity	Small-magnitude seismic events potentially associated with injection-induced stress changes.
Traffic-light system (TLS)	Operational framework linking seismic thresholds to actions (green/yellow/red).
CBL	Cement Bond Log: logging tool to evaluate cement quality and zonal isolation.
USIT	Ultrasonic Imager Tool: ultrasonic imaging to assess casing/cement condition and integrity.
Gravimetry (time-lapse)	Repeat gravity measurements to infer subsurface density changes related to CO_2/brine substitution.
EM / CSEM	Electromagnetic methods (including controlled-source EM) to detect resistivity changes associated with CO_2 saturation.
CO_2 stream monitoring	Sampling and analysis of injected CO_2 composition/impurities and physical properties for compliance and integrity.
Tracer pulse	Injection of a chemical/isotopic tracer as a contingency to diagnose migration/leakage pathways.
History matching	Iterative calibration of the dynamic model to monitoring observations (pressure, geophysics, etc.).

Table 17 Glossary

6. Lusitanian Basin (Portugal)

6.1 Introduction

This chapter presents the technical and operational definition of the CO_2 injection pilot foreseen for the Lusitanian Basin offshore Portugal, developed within the framework of the PilotSTRATEGY project. The objective is to describe the conceptual design, construction, testing, operation and maintenance of the offshore CO_2 storage site at a level of detail consistent with the requirements of a pilot-stage permit dossier and including the CO_2 transport logistics and conditioning. The scope of the description reflects the non-commercial and temporary nature of the pilot, while adopting technical standards and operational practices consistent with offshore oil and gas activities, for the well components, and best-practices from existing offshore CO_2 storage projects.

The Portuguese pilot presents a number of distinctive characteristics compared to onshore cases addressed elsewhere in the project, namely:

- An offshore location in shallow water (~85 m), within the Portuguese maritime space
- A ship-based injection concept, avoiding permanent offshore surface facilities
- Limited injection volumes (<100 kt of CO_2) over the pilot duration
- Reliance on existing maritime and port infrastructure, notably the Port of Figueira da Foz, for logistics and operational support

The chapter integrates information from legacy offshore exploration activities, notably the analysis of nearby offset wells, with the conceptual injection well design, drilling and testing programmes, well operations, monitoring, HSE and permitting considerations. Particular emphasis is placed on ensuring well integrity, containment performance and operational safety, while maintaining proportionality to the pilot scale. These are addressed in section 6.2and 6.3.

Sections 6.4 to 6.7, as for the other PilotSTRATEGY regions, deal with the aspects related to the design of the pilot itself, rather than strictly the injection well. Thus, section 6.4 describes the CO_2 intermodal transport logistics; section 6.5 details the CO_2 conditioning process and requirements from the capture facility to the wellhead injection condition and is supplemented by Annex 2 covering the thermodynamic analysis; section 6.6 provides the qualitative risk assessment for the pilot and includes the Risk Register as Annex 3 and section 6.7 presents the MMV plan.

6.2 Technical specifications of the CO_2 injection pilot

The objective of this section is to describe the conceptual design, construction, testing, operation and maintenance of the offshore CO_2 injection well foreseen for the Lusitanian Basin pilot, in a level of detail consistent with the requirements of a permit dossier at pilot stage. The description is adapted to the specific characteristics of the Portuguese case, namely offshore location, ship-based injection, limited injection volume and the absence of permanent surface facilities.

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6.2.1 Offset well analysis

The Lusitanian Basin has experienced multiple offshore hydrocarbon exploration campaigns, with nine wells drilled in the offshore area of interest at water depths of 43–133 m (Table 18 Summary of nearby offset wells). This set includes the Dourada-1 well, which constitutes the closest legacy well (~11 km) to the injection site considered in the pilot context. While not designed for CO_2 storage, Dourada-1 offers relevant regional insight into stratigraphy, pressure conditions and drilling performance.

Well Name	Abrev. Name	Operator	Spud year	Total depth (m MD)	Water Depth (m)
Sardinha	13C-1	Shell	1974	2801.0	83.0
Dourada-1C	Do-1C	Sun Oil	1974	3668.0	84.1
Moreia-1	Mo-1	Sun Oil	1974	2144.0	44.8
Espadarte-1	14A-1	Shell	1975	2862.0	43.0
Espadarte-1A	14C-1A	Shell	1975	2142.0	133.0
Cachucho-1	16A-1	Shell	1975	2655.0	125.0
Espadarte-2	14A-2	Shell	1976	2290.0	67.0
Faneca-1	Fa-1	Esso	1976	2599.9	112.0
Sardinha-1	13E-1	Shell	1977	2044.0	107.0

Table 18 Summary of nearby offset wells

6.2.1.1 Offset well analysis – Dourada-1 well

The Dourada-1 exploration well was drilled offshore Portugal by Portugal Sun Oil Company, approximately 29 km northwest of Figueira da Foz, in 84 m of water depth. The well was drilled under historical standards and permanently abandoned, reaching a total depth (TD) of 3,668 m (12,032 ft) and represents one of the earliest deep offshore drilling attempts in Portuguese waters.

- Spud date: 14 December 1974
- Completion / abandonment date: 29 March 1975
- Water depth: 84 m
- Total depth: 3,668 m (12,032 ft)

The Dourada-1 drilling campaign was characterized by significant operational challenges, both at the surface and downhole, which had a material impact on overall efficiency and duration.

A total of three attempts to spud the well were required, due to a combination of hole problems, mechanical issues, and operational constraints. As a result, the well location had to be relocated on each attempt, highlighting early limitations in offshore positioning, seabed preparation, and well control practices at the time. The final well, Dourada-1C, was drilled and ultimately abandoned after 84 days of drilling operations, reaching TD at 3,668 m.

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A major contributor to non-productive time was the use of a rig without a motion compensator, which significantly limited operations under offshore heave conditions. As a consequence, approximately 20 days were lost due to weather-related and motion-induced downtime. Activities affected included:

- Weight-on-well (WOW) limitations
- Tripping operations
- Pulling and running the marine riser

These constraints underline the strong dependency of early offshore drilling campaigns on benign weather windows and the lack of technological mitigation measures that are standard in modern offshore rigs.

When including drilling, downtime, and abandonment activities, the total operational duration reached approximately 104 days. Despite the operational difficulties, the Dourada-1 well provided valuable geological and operational data for the Portuguese offshore, contributing to the understanding of basin characteristics and highlighting key technological gaps relevant to offshore exploration at the time.

The Dourada-1 experience illustrates several aspects that are relevant when framing drilling and seismic planning in the Portuguese offshore context:

- High sensitivity of offshore operations to weather and sea state, particularly in the absence of motion-compensated systems
- Elevated operational risk during early offshore exploration campaigns, including wellbore stability and mechanical reliability issues
- Importance of rig capability selection and contingency planning to manage non-productive time

Legacy wells such as Dourada-1 are therefore treated as elements of concern in the risk assessment and MMV design, despite long-term CO_2 modelling suggests that the plume does not reach the well. Their potential influence is addressed through conservative pressure management, baseline seismic imaging, continuous well pressure monitoring and seabed surveillance. No offset production or injection wells are present in the immediate vicinity of the planned injection location, and no re-entry or re-use of Dourada-1 is foreseen in the pilot configuration.

6.2.2 Well design

The pilot foresees the drilling of one dedicated offshore CO_2 injection well, designed specifically for pilot-scale injection and permanent monitoring. The well is assumed to be vertical or slightly deviated, depending on final positioning constraints.

The conceptual well architecture includes:

- Conductor casing, set and cemented to seabed, providing structural support and isolation of shallow sediments
- Surface casing, cemented to seabed, ensuring well control and isolation of upper formations
- Intermediate casing, cemented across sealing formations to guarantee zonal isolation

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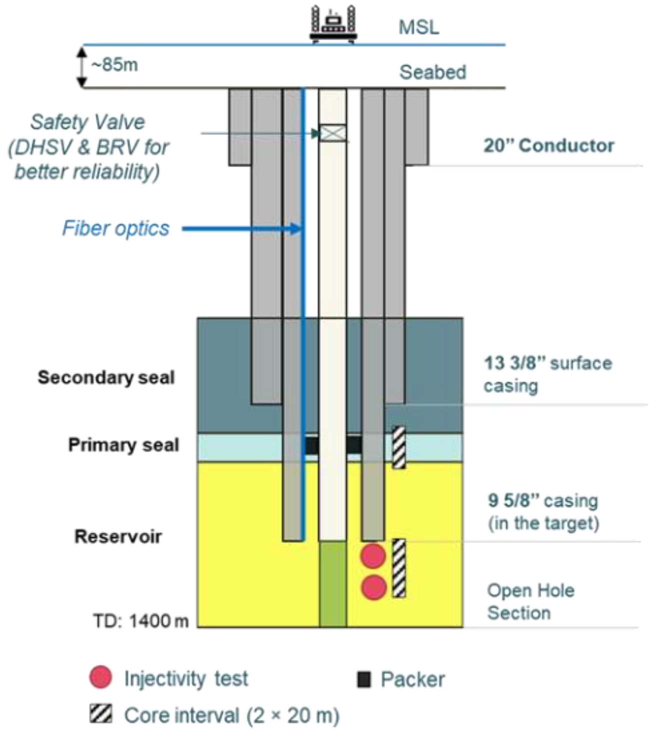
- Injection casing or liner, set across the storage reservoir interval and completed for CO_2 injection

The injection well is designed with a conservative casing program appropriate for pilot-scale offshore CO_2 injection and consistent with standard well-integrity practices. The well is drilled in a water depth of approximately 85 m, reaching a total measured depth of around 1,400 m. The planned total depth provides adequate vertical separation and integrity margins for two injection intervals located at approximately 1,025 m and 1,155 m depth (Figure 27 - Injection well design (MSL – Mean sea level;



TD - Total depth; DHSV – Downhole safety valve; BRV – Backup safety valve)).

Figure 27 - Injection well design (MSL – Mean sea level; TD - Total depth; DHSV – Downhole safety valve; BRV – Backup safety valve)

A permanent wellhead will be installed for all drilling and completion operations, with a blowout preventer (BOP) stack mounted on top during drilling activities. The wellhead constitutes the primary surface pressure-containing and structural interface of the well, providing support for casing and tubing strings and enabling controlled management of wellbore fluids between the subsurface and surface facilities.

- Well construction starts with the installation of a 20" conductor casing, set at approximately 145 m MD. This casing provides structural support at the seabed and isolates shallow unconsolidated sediments. The corresponding open-hole interval is approximately 60 m. Logging-while-drilling (LWD) measurements in this section support early stratigraphic control and lithological characterization;
- A 13 3/8" surface casing is subsequently run and set at approximately 700 m MD, isolating the upper geological formations and ensuring well control. This section includes an open-hole interval of approximately 555 m. LWD measurements acquired in this interval provide

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continuous stratigraphic control, support the velocity model calibration and enable seismic well tie;

- The reservoir and caprock interval is drilled in the 9 5/8" section, with the casing or liner set at approximately 1,150 m MD. This section corresponds to an open-hole interval of approximately 450 m and represents the critical interval for reservoir characterization and injectivity assessment. Comprehensive LWD and wireline data acquisition are focused on this section.

The well reaches total depth at approximately 1,400 m, with the final ~100 m drilled to ensure adequate exposure of the target reservoir interval and reliable pressure communication.

The completion design foresees a 9 5/8" slotted liner across the injection interval, allowing controlled injection while maintaining hydraulic communication with the formation. All casing strings are assumed to be cemented using CO_2-compatible cement systems, with cement placement and zonal isolation verified through dedicated cement-evaluation logging.

This casing program provides the structural integrity and operational flexibility required for safe pilot-scale injection, supports the planned logging and testing activities, and is compatible with the permanent well-monitoring systems foreseen in the MMV plan.

Casing Size (")	MD (m)	OH (m)
WD	85	
20	145	60
13 3/8	700	555
9 5/8"	1150	450
TD	1400	50

Table 19 - Well casing program showing casing sizes, measured depth (MD) and open hole (OH) intervals from water depth to total depth

All casing strings are assumed to:

- Use CO_2-compatible steel grades;
- Be cemented with CO_2-resistant cement systems, particularly across the caprock and injection interval;
- Be designed to accommodate permanent fibre-optic cable installation (DAS/DTS) and downhole pressure and temperature sensors.

The wellhead and subsea tree are designed for temporary connection to a ship-based injection system, without permanent topside facilities.

6.2.3 Well time

The drilling and completion campaign is planned as a single offshore operation, executed using a jack-up drilling unit, which provides a stable working platform for accurate drilling and well

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completion operations under the shallow-water conditions of the Lusitanian Basin (~85 m water depth). Indicative phases include:

- Rig mobilisation and site positioning
- Conductor installation
- Drilling and casing of surface and intermediate sections
- Drilling of the reservoir section in open hole
- Logging, coring and testing operations
- Completion, installation of monitoring systems and subsea wellhead
- Rig demobilisation

Based on comparable offshore wells of similar depth and complexity, the indicative drilling and completion duration is assumed to be of the order of 20-30 days, excluding weather standby and mobilization-demobilization. Final duration will depend on metocean conditions, rig availability, and final well depth.

Well timings are based on the most-likely case (P50). The following assumptions were made in order to provide this time estimate, consistent with offshore oil & gas industry standards and with previous project deliverables:

- A ~1,000 hp jack-up drilling rig is considered for the operation, as its capabilities are well within the requirements of the proposed well design and total depth (~1,400 m MD)
- International mobilization is assumed, with an indicative mobilization duration of ~45 days, reflecting limited regional availability of suitable rigs and standard offshore contracting practice
- The daily rig rate shown is preliminary and non-binding, derived from offshore benchmarks and internal reference data. The estimate needs to be subject to full market enquiry and procurement due diligence if the project advances beyond the pilot definition stage
- Injectivity testing services (DST with water injection) are included in the work program
- Based on offset wells and the Portuguese pilot design, a mechanical well configuration is proposed with casing strings of 20” (conductor), 13 3/8” (surface) and 9 5/8” (injection casing)
- All casing strings are assumed to use CO_2-compatible steel grades in accordance with offshore injection-well standards, with materials selected to withstand corrosion associated with CO_2-rich environments
- Conventional coring is planned across the reservoir and seal intervals. Coring time estimates are derived from offshore analogue wells of similar depth and lithology
- A CO_2-resistant cement slurry is required, particularly across the caprock and casing shoes, to ensure long-term zonal isolation and well integrity

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- If the injectivity test is positive and the well is retained for future use, a completion upgrade or re-completion could be implemented at a later stage using a workover rig. This operation is not included in the present T&C estimate
- For plug and abandonment (P&A), the following assumptions apply:
  - The base case assumes permanent P&A at the end of the pilot
  - The P&A assumes good cement behind the 9 5/8” and 13 3/8” casings. Abandonment operations include cement plugs across the open-hole reservoir interval, caprock and upper well sections, and removal of the wellhead in accordance with offshore oil & gas best practice and regulatory requirements
  - If the well becomes a keeper, the P&A scope and duration would be significantly reduced through temporary abandonment

The estimated drilling and completion activities are approximately 20-30 days of duration, excluding contingency and rig mobilization and demobilization. The estimated duration for data acquisition, including logging, coring, and preliminary injectivity testing is approximately 15 days. No permanent offshore platform or fixed surface infrastructure is required.

6.2.4 Logging, coring, and injectivity tests

The well logging and data-acquisition programme has been defined to support stratigraphic control, seismic calibration, reservoir characterisation, geomechanical understanding and verification of well integrity, while remaining proportionate to the scale of the offshore pilot. The programme combines logging-while-drilling (LWD) measurements in the upper sections with a comprehensive wireline acquisition suite across the 9 5/8” section intersecting the storage reservoir.

The planned data-acquisition programme includes a drill-stem test (DST), with an injectivity test performed using water to assess reservoir performance prior to CO_2 injection. Wireline operations are estimated to require approximately 10 days, including around 3 days dedicated to the injectivity test. The conceptual completion design foresees a 9 5/8” slotted liner across the injection interval, allowing controlled injection while enabling effective pressure monitoring and well testing.

6.2.4.1 Logging-while-drilling (LWD)

LWD measurements are planned across the 20” conductor, 13 3/8” surface casing and 9 5/8” reservoir section, ensuring continuous data acquisition during drilling and early reduction of subsurface uncertainty.

In the 20” conductor section, Gamma Ray and resistivity (GR/RES) measurements are acquired to provide basic control on stratigraphy and lithology. In addition, compressional and shear sonic measurements (P/S) are included to improve the field velocity model and de-risk depth-conversion uncertainties at the earliest drilling stage.

In the 13 3/8” surface casing section, the LWD suite comprises GR/RES measurements for stratigraphic and lithological control, sonic (P/S) measurements to further constrain the velocity model, and density/neutron logs to support seismic well tie and improve the calibration of seismic interpretation.

In the 9 5/8” section intersecting the target reservoir, LWD measurements include GR/RES for stratigraphic control, sonic (P/S) measurements to refine velocity information, density/neutron logs for seismic tie, and nuclear magnetic resonance (NMR) measurements. NMR data are considered

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critical for reservoir characterization, allowing direct estimation of porosity and permeability and providing early insight into injectivity potential prior to testing.

6.2.4.2 Wireline logging and coring – 9 5/8" section

A dedicated wireline logging program is planned across the 9 5/8" open-hole section, complementing the LWD dataset with high-resolution measurements and direct rock sampling.

The wireline program includes:

- Vertical Seismic Profile (VSP) / checkshot acquisition to establish a robust time-depth relationship and support seismic-to-well calibration
- Resistivity logs and resistivity image logs to characterize lithology, bedding, fractures and small-scale heterogeneities
- Magnetic resonance logging with lithoscanner to refine porosity, permeability and mineralogical interpretation and to complement LWD-NMR data
- Sidewall coring, providing rock samples for laboratory petrophysical, geochemical and geomechanical analyses
- Acoustic image and pressure measurements, supporting geomechanical interpretation and in-situ pressure control
- Sonic scanner measurements, improving elastic property estimation and integration with geomechanical and seismic models
- Formation fluid sampling, planned as a contingency option, to characterize formation fluids and support injectivity and flow-assurance assessment if required
- Cement evaluation logging (full length) to verify cement placement and zonal isolation

6.2.5 Completion and injectivity testing

The conceptual completion design foresees a 9 5/8" casing set above the reservoir, with the injection intervals located in the open-hole section below the casing shoe, extending down to approximately 1,400 m MD. Two reservoir intervals, located at approximately 1,025 m and 1,155 m depth, are considered for injectivity assessment within this open-hole section. This configuration allows direct hydraulic communication with the reservoir while preserving a simple and flexible completion concept appropriate for a pilot-scale offshore well.

An injectivity test is planned prior to CO_2 injection and will be conducted as part of a drill-stem test (DST) using water as the injection fluid. The primary objective of the test is to confirm the ability of the reservoir to accept injected fluids under controlled pressure conditions, thereby validating the feasibility of pilot-scale injection and establishing an initial operational envelope for subsequent CO_2 injection.

The injectivity test is designed in accordance with standard offshore oil & gas practice for appraisal and injection wells and comprises:

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- Injection of formation-compatible water or brine into the open-hole reservoir section, targeting one or both injection intervals as operationally appropriate
- Controlled injection periods, potentially at more than one flow rate, followed by shut-in (fall-off) periods, to observe the pressure response of the well–reservoir system

The test is not intended to induce hydraulic fracturing or to deliberately exceed formation-integrity limits. Injection rates and pressures will be managed conservatively to remain within the expected reservoir and well-integrity envelope.

Downhole and surface pressures will be continuously monitored during injection and subsequent shut-in periods. The recorded pressure response will be used, where data quality and test duration allow, to derive indicative information on:

- Reservoir injectivity behaviour at the tested intervals
- Near-wellbore conditions
- Pressure communication within the reservoir

Pressure build-up and fall-off behaviour will be observed over a sufficiently long period to support qualitative and, where possible, quantitative interpretation, recognising that the level of diagnostic resolution depends on reservoir properties, test duration and the operational constraints typical of offshore pilot operations.

A successful injectivity test, demonstrating stable pressure behaviour and the absence of abnormal pressure response, is a mandatory prerequisite for proceeding with CO_2 injection during the pilot phase.

The combined logging, coring and testing programme provides the minimum dataset required to support pilot-stage injection, reduce uncertainty in reservoir performance and verify well integrity, while remaining scalable for potential future phases.

6.2.6 Well operations and logistics

Injection operations are performed using a ship-based injection concept, with CO_2 transported, conditioned and injected directly from a dynamically positioned vessel. Key operational features include:

- Temporary subsea connection between the vessel injection system and the wellhead
- No permanent offshore surface facilities
- Injection performed in discrete batches aligned with the transport cycle
- Continuous monitoring of pressure, temperature and flow during injection

Operational limits are defined by metocean conditions, hose integrity limits and allowable wellhead pressure.

6.2.7 Well maintenance plan

Given the limited duration and scale of the pilot, the well maintenance strategy focuses on continuous integrity surveillance, rather than routine mechanical intervention. The maintenance plan includes:

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- Continuous monitoring of wellhead and downhole pressure and temperature
- Annulus pressure monitoring to detect early integrity issues
- Permanent Distributed Acoustic Sensing (DAS) for detection of abnormal flow, strain or microseismic signals
- Periodic review of monitoring data within the MMV framework

No major workover activities are foreseen during the pilot, provided monitoring confirms normal behaviour.

6.2.8 Plug and Abandonment assumptions

For the base-case pilot configuration, the injection well is assumed to be permanently abandoned at the end of the pilot, unless a future commercial phase is authorised. P&A assumptions include:

- Verification of well integrity prior to abandonment
- Placement of cement plugs across the injection interval, caprock and upper well sections
- Removal of subsea wellhead and restoration of seabed conditions in accordance with Portuguese offshore regulations

If the well is retained for future use, a temporary abandonment configuration may be adopted, significantly reducing P&A scope and cost.

6.2.9 Regulatory and permitting framework

Well operations for the Portuguese pilot are developed within the national legal framework for offshore geological CO_2 storage, as transposed from European legislation and described in deliverable D4.7. The pilot well is located in shallow offshore waters within the Portuguese maritime space, and all well-related activities are therefore subject to both subsurface permitting and maritime spatial planning requirements.

The pilot phase is explicitly framed as a scientific research activity, with a total injected CO_2 mass below 100 kt and is therefore exempt from the full storage concession regime established under Decree-Law No. 60/2012. Nevertheless, drilling and testing operations remain subject to environmental assessment, maritime permitting and safety authorisations, in line with offshore oil & gas practice.

Competence for permitting and oversight is distributed as follows:

- DGEG (Direção-Geral de Energia e Geologia): authority for geological exploration activities and subsurface works, including exploration well drilling
- APA (Agência Portuguesa do Ambiente): competent authority for Environmental Impact Assessment (EIA)
- DGRM (Direção-Geral de Recursos Naturais, Segurança e Serviços Marítimos): authority for maritime safety, navigation and private use of maritime space (TUPEM)

6.2.10 Operational permitting

The drilling and testing of the offshore pilot well is authorized under the pilot-phase permitting pathway, which applies to non-commercial CO_2 storage projects developed for scientific research purposes. Key permitting elements applicable to the well operations include:

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- Exploration license for well drilling, issued by DGEG, covering the execution of a single offshore validation well
- Environmental Impact Assessment (EIA), coordinated by APA, addressing drilling, testing and temporary offshore activities associated with the well
- Title for the Private Use of Maritime Space (TUPEM), issued by DGRM, granting the right to temporarily occupy a defined offshore area for drilling and testing operations

For pilot-scale scientific projects, the TUPEM may be issued as an authorization, rather than a license or concession, allowing temporary and non-commercial use of the maritime space and, where applicable, exemption from an allocation plan, subject to governmental decision.

The well operations are executed without the installation of any permanent offshore surface infrastructure and do not require a fixed platform or long-term seabed occupation. Under the granted permits, well operations would comprise:

- Mobilization and positioning of a jack-up drilling unit
- Drilling and construction of a single offshore well to approximately 1,400 m MD
- Acquisition of logging, coring and pressure data
- Execution of a water-based injectivity test as part of a drill-stem test (DST)
- Temporary completion and monitoring activities required to support pilot-stage assessment
- Permanent or temporary abandonment of the well, depending on test results and regulatory conditions

All drilling and testing activities are conducted in accordance with offshore oil & gas safety standards, including approved well programmes, emergency response plans and marine safety procedures reviewed by DGRM.

The injectivity test forms part of the exploration programme and is executed exclusively to verify reservoir acceptance and pressure behavior. It does not constitute commercial injection and does not trigger storage-concession requirements.

6.2.10.1 Transition for future phases

Successful execution of the pilot well and injectivity test provides the technical basis for potential future phases. Any transition to long-term CO_2 injection, injection volumes exceeding 100 kt, or installation of permanent offshore infrastructure, would require a separate permitting process, including:

- Application of the full Decree-Law No. 60/2012 storage-concession regime, to allow injection volume upscaling
- Approval of a comprehensive monitoring and corrective-measures plan
- Updated EIA covering commercial-scale operations and associated surface and offshore facilities

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Such future phases are out of scope of the present pilot and are not covered by the permits described in this section.

6.2.10.2 Planning and logistics of well operations

Given the proximity of the offshore injection site to the coast and the availability of suitable port infrastructure, the Port of Figueira da Foz is envisaged as the primary logistics base for the offshore well operations. The port will act as the onshore hub supporting drilling, testing and abandonment activities, in line with standard offshore oil & gas practice for shallow-water operations.

The logistics base at the port constitutes a critical component of the well-delivery system, providing the interface between suppliers, service companies, marine logistics and the offshore drilling unit. Its role is to ensure that all materials, equipment and consumables required for the campaign are available in a timely, safe and cost-efficient manner, thereby supporting operational continuity and minimising Non-Productive Time (NPT).

The adoption of a port-based logistics solution is facilitated by:

- The short sailing distance between Figueira da Foz and the offshore well location
- The temporary nature of the pilot operations
- The absence of permanent offshore surface infrastructure
- The option for direct offshore injection, which limits onshore handling requirements

6.2.11 Logistics

6.2.11.1 Inventory management and control

Port-based logistics facilities would be used to store and manage casing, wellhead components, drilling tools, spare parts, drilling fluids, additives and service-company equipment. Inventory levels would be planned to match the drilling schedule and marine supply frequency. Standard inventory-management systems will be used to track material movements, critical spares and hazardous materials, ensuring full traceability and compliance with applicable safety and environmental regulations.

6.2.11.2 Material reception, verification and quality assurance

All materials delivered to the port logistics base will undergo documented inspection and verification prior to offshore shipment. This includes visual and dimensional checks, review of certification and compliance documentation (e.g. material certificates, test reports and safety data sheets), and confirmation of conformity with the approved well programme.

Non-conforming materials will be identified and managed through established quality-assurance procedures, ensuring that only compliant equipment is mobilised offshore.

6.2.11.3 Marine logistics. vessel coordination and operational support

The port logistics base would coordinate all marine logistics between shore and the offshore drilling unit. This includes planning and scheduling of supply-vessel movements, load-out and back-load operations, and coordination with port authorities and marine contractors.

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All lifting and handling operations would be conducted in accordance with approved lifting plans and maritime safety requirements. Returned equipment, empty containers, used tools and waste would be received at the port, documented and routed for inspection, reuse or disposal.

Critical spares and contingency equipment would be staged at the port to support unplanned operational events, such as equipment failures or well-control-related scenarios. The port logistics base will serve as the primary onshore coordination point in case of incidents or emergencies, enabling rapid mobilisation of additional equipment or services to the offshore unit when required.

During offshore drilling and testing operations, the port logistics base would operate on a 24/7 basis, ensuring continuous support to the offshore unit. The facilities will be equipped with appropriate lifting and handling equipment, including cranes and forklifts, to safely manage tubulars, containers and heavy equipment. Staffing levels, operating procedures and HSE arrangements will be aligned with offshore operational requirements and emergency-response plans.

By using the Port of Figueira da Foz as the logistics base, the project leverages existing infrastructure to support offshore well operations in a simple, robust and cost-effective manner. The port-based logistics setup supports safe and efficient material management, marine coordination and contingency response, while remaining fully compatible with the temporary, pilot-scale nature of the Portuguese offshore CO_2 injection project.

6.2.11.4 Waste management

In accordance with Portuguese and EU environmental regulations, the port logistics base would manage the segregation, documentation and back-haul of waste generated offshore. This includes drill cuttings containers, used chemical drums, scrap materials and other operational waste. Waste handling and disposal will follow approved waste-management procedures and will be performed through licensed contractors operating from the port.

6.2.12 Summary of well logging, coring and testing plan

The logging, coring and testing programme for the Portuguese offshore pilot well is designed to provide a fit-for-purpose dataset to (i) confirm reservoir and seal characteristics, (ii) verify well integrity, and (iii) de-risk pilot-scale injection prior to any CO_2 operations. The programme is integrated with the drilling sequence and is focused on the open-hole reservoir section below the 9 5/8” casing, where the two planned injection intervals are located at approximately 1,025 m and 1,155 m depth, with total depth around 1,400 m MD.

6.2.12.1 Logging and coring programme (data acquisition)

Logging is implemented through a combination of logging-while-drilling (LWD) and wireline logging, providing continuous real-time measurements during drilling and higher-resolution formation evaluation after drilling to TD. The logging scope is selected to support lithostratigraphic correlation, seismic calibration, reservoir characterisation (including porosity and permeability indicators), and integrity verification, consistent with an offshore appraisal / pilot injection well.

Coring is planned across the seal section and selected reservoir intervals in the open-hole section, subject to operational feasibility, to provide direct samples for laboratory measurements supporting injectivity and containment assessment (e.g., porosity/permeability, capillary and flow properties, mineralogical controls). The coring scope is intentionally proportionate to the pilot stage and offshore execution constraints.

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Wireline operations are expected to be of the order of ~10 days, including ~5 days associated with the injectivity test window, reflecting the integrated nature of acquisition and testing in a single offshore campaign.

6.2.12.2 Testing programme – water-based injectivity test (DST)

A water-based injectivity test is planned prior to CO_2 injection and will be executed as part of a Drill-Stem Test (DST) in the Torres Vedras Group reservoir section. The test is designed to confirm that the well–reservoir system can accept injection under controlled conditions and to establish an initial operational envelope for the pilot.

The dynamic modelling basis used in the project indicates a P50 optimal injection rate of ~0.254 Mt/yr per well, which provides a benchmark for the expected order of magnitude of injectivity performance. The injectivity test is therefore structured to validate reservoir acceptance and pressure response at the pilot scale, recognising that the test provides an operational confirmation rather than a commercial capacity proof.

The injectivity test is designed to acquire, where data quality and test duration allow, the following information:

- Initial reservoir pressure and temperature at the tested interval(s)
- Injectivity behaviour and pressure response under controlled injection
- Near-wellbore condition indicators (e.g., skin effects)
- Indicative formation transmissibility (kh) and pressure communication behaviour
- Optional brine sampling for basic fluid characterisation (where operationally justified)

The injectivity test will be implemented using standard offshore well-test practice, combining controlled injection and shut-in periods:

- A multi-rate (rate-step) injection sequence to characterise injectivity behaviour
- One or more fall-off (shut-in) periods to observe pressure decline and support pressure-transient interpretation
- Where required and permitted, a conservative step-rate element may be used to help bracket formation parting behaviour, without making fracture initiation an objective of the pilot

The test will target one or both of the open-hole injection intervals (~1,025 m and ~1,155 m) depending on final operational configuration and well conditions. Injection pressures and rates will be managed conservatively to remain within a well-integrity and safety envelope appropriate for offshore operations.

The DST string is expected to include downhole pressure/temperature gauges (with backup) and a shut-in capability to enable stable injection and fall-off recording. Continuous acquisition of injection rate, pressure and temperature will be maintained during injection and shut-in. The test duration will be set to capture meaningful pressure behaviour (qualitative and, where possible, quantitative), recognising that diagnostic resolution depends on reservoir properties and offshore operational constraints.

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Injection is performed using formation-compatible water or brine. Where compatibility risks exist, inhibitors may be used to minimise scaling or adverse interactions between injected water and formation brine. Flowback handling capacity and offshore waste management are planned within the campaign logistics framework.

A successful injectivity test, demonstrating stable pressure behaviour and the absence of abnormal response, is a mandatory prerequisite to proceed to CO_2 injection in the pilot. The overall logging, coring and testing programme is designed to be scalable: if pilot results justify progression, additional testing, monitoring upgrades or completion changes can be implemented in later phases under the applicable permitting framework.

6.3 Health, Safety & Environment

6.3.1 Health Safety Environment Management System

Health, Safety and Environment (HSE) management for the Portuguese offshore pilot is structured in accordance with offshore oil and gas industry standards and best practices, adapted to the pilot-scale and non-commercial nature of the project. The HSE framework is designed to ensure protection of personnel, the marine environment and project assets throughout drilling, testing, injection and well abandonment activities.

Overall HSE accountability resides with the project operator, who is responsible for establishing and enforcing the project-specific HSE Management System (HSE-MS). All contractors involved in offshore drilling, marine operations, logistics and monitoring are required to operate under HSE systems equivalent to offshore O&G standards and fully integrated with the project HSE-MS.

The HSE management system/plan includes:

- Robust risk management process
- Clear governance, roles, responsibilities and accountabilities. This includes:
    - A designated Project HSE Manager with authority to stop operations if unsafe conditions are identified
    - Defined interfaces between the operator, drilling contractor, marine contractors and port authorities
    - Personnel assigned to the Project who meet the required competency standards
- Explicit control of work
- Mandatory offshore safety training, inductions, HSE drills and toolbox talks covering drilling operations, marine safety and CO_2-related hazards
- Systematic performance monitoring. This includes verification of critical controls, audits/inspections, and incident reporting and investigation.
- HSSE/ESMP Contractor Requirements
- Emergency Response Plan (ERP)

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6.3.2 Risk management

Risk reduction is based on a hierarchical control philosophy, prioritising hazard elimination and risk reduction through design, followed by operational controls and emergency preparedness. Key risk-reduction principles include:

- Risk assessment and barrier management
- Identification and management of HSSE-critical activities and equipment
- Conservative well design and materials selection suitable for CO_2 service
- Limitation of operations to pilot scale (<100 kt CO_2) and to short-duration activities
- Avoidance of permanent offshore infrastructure
- Use of proven offshore technologies and equipment
- Integration between operational planning, MMV data and real-time monitoring
- Strong SIMOPS (Simultaneous Operations) execution during complex phases

Risk-reduction measures are reviewed before each critical operation (drilling, DST, injection start-up, abandonment) and updated as required based on operational feedback.

6.3.3 Hazard Identification

Hazard identification is conducted systematically for all pilot activities, using standard offshore risk-assessment tools (e.g. HAZID, task-based risk assessments). Identified hazards include, but are not limited to:

Offshore and marine hazards

- Adverse weather and sea-state conditions
- Marine traffic interaction and collision risk
- Lifting and crane operations offshore (when applicable)
- Vessel positioning and station-keeping
- Dropped objects

Drilling and well-control hazards

- Overpressure, kick and loss of well control
- Loss of well integrity during drilling or testing
- Failure of well barriers during injection or abandonment

CO_2-specific hazards

- Release of CO_2 during testing or injection
- Asphyxiation risks in confined or semi-confined spaces
- Corrosion and material degradation

Environmental hazards

- Seabed disturbance during drilling
- Discharge of cuttings and fluids
- Disturbances to the water column during offshore operations

Hazards are assessed in terms of likelihood and consequence, and appropriate controls are defined and implemented.

6.3.4 Environmental, Social & Health Impact Assessment

The offshore pilot is subject to Environmental Impact Assessment (EIA) under Portuguese legislation, coordinated by the Portuguese Environment Agency (APA). The assessment considers all temporary impacts associated with offshore drilling, marine operations and pilot injection. The EIA addresses:

- Impacts on the seabed and benthic habitats
- Effects on the water column, including turbidity and noise
- Interaction with fisheries and navigation routes
- Occupational health risks for personnel

Due to the offshore location, temporary nature of operations and limited injection volume, no significant long-term environmental or social impacts are anticipated (as described in the deliverable D4.8). Mitigation measures and monitoring actions are defined and linked to the MMV programme, described in the following chapters.

6.3.5 Prevention and Control Measures

Prevention and control measures implemented for the pilot include:

- Offshore-certified blowout preventers, safety valves and pressure-control systems
- Real-time monitoring of pressure and temperature during drilling, testing and injection
- Approved operating procedures for all critical tasks
- Controlled handling and transfer of CO_2 from the capture points to the port, and from the port to the offshore storage site
- Waste management and discharge controls in line with offshore regulations
- Regular safety inspections, audits and HSE drills

These measures are designed to prevent incidents and minimise consequences should deviations occur.

6.3.6 Emergency management

An Emergency Response Plan (ERP) is established for the Portuguese offshore pilot to ensure a coordinated, rapid and effective response to incidents with potential impacts on personnel safety, the marine environment or the integrity of the well and associated systems. The ERP is designed in accordance with offshore oil and gas best practice, while remaining proportionate to the pilot-scale, temporary and non-commercial nature of the project.

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The ERP applies to all offshore activities associated with the pilot, including drilling and completion, injectivity testing, ship-based CO_2 injection, marine logistics and well abandonment. It is fully integrated with contractor emergency procedures, port emergency arrangements at Figueira da Foz, and the response structures of the competent maritime authorities.

Emergency management follows a clear command and control structure, integrated with that of contractors and relevant public authorities. Key elements include:

- A designated Offshore Incident Commander (OIC) on the drilling unit or vessel, responsible for immediate on-site response
- An Onshore Emergency Coordinator (OEC), based at the project logistics base (Port of Figueira da Foz), responsible for coordination with authorities and external resources
- Defined escalation criteria and communication pathways between offshore and onshore teams

The ERP relies on early detection, rapid escalation and predefined response actions supported by multiple monitoring layers (well parameters, operational data, marine and meteorological monitoring, MMV systems).

6.3.6.1 Emergency scenarios (ERP)

The ERP addresses a range of credible emergency scenarios identified through hazard and risk analysis, described in Table 20- Main emergency scenarios considered.

Emergency category	Representative scenarios	Primary risks
Well control & subsurface	Loss of primary barrier, abnormal pressure response, loss of integrity during testing or injection	Personnel safety, loss of containment
CO_2-related	Accidental release during testing or injection, exposure to high CO_2 concentrations	Asphyxiation, equipment damage
Offshore & marine	Vessel collision, loss of station, lifting accidents, man-overboard	Injury, asset damage
Environmental	Accidental discharge, seabed disturbance beyond expected footprint	Marine environmental impact
Weather & external	Extreme metocean conditions, reduced vessel operability	Escalation of other incidents

Table 20- Main emergency scenarios considered

These scenarios were identified through hazard identification and offshore risk-assessment exercises and form the basis for response planning.

6.3.6.2 Emergency response principles and actions

For all scenarios, the ERP applies the following response priorities:

- Protection of human life

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- Prevention of incident escalation
- Minimisation of environmental impact
- Stabilisation and recovery of safe conditions

Response actions include immediate shutdown of operations when required, activation of well-control and safety systems, isolation of affected equipment, and evacuation or shelter-in-place of personnel depending on conditions. CO_2-related incidents are managed through controlled depressurisation, exclusion zones and continuous gas monitoring.

Communication protocols, escalation thresholds and reporting timelines are clearly defined to ensure regulatory compliance and effective coordination (Table 21).

Role	Location	Key responsibilities
Offshore Incident Commander (OIC)	Offshore unit / vessel	Immediate incident control, personnel safety, activation of emergency procedures
Onshore Emergency Coordinator	Port of Figueira da Foz	Coordination with authorities, logistics support, external communication
Drilling / Marine Contractor Leads	Offshore / onshore	Technical response, equipment isolation, safe shutdown
Maritime Authorities (DGRM)	National / regional	Search and rescue, navigation safety, marine pollution response
Port Authority & Emergency Services	Onshore	Medical response, evacuation support, spill response

Table 21- Emergency response roles and coordination

Evacuation and rescue arrangements are designed in line with offshore standards and take advantage of the short distance between the offshore site and the coast. The ERP includes procedures for medical response offshore, transfer of injured personnel, and coordination with onshore medical facilities. Search and rescue operations are conducted in coordination with maritime authorities.

All personnel involved in offshore operations receive training on emergency procedures relevant to their role. Emergency drills and exercises, including offshore – onshore coordination, are conducted periodically to verify readiness and identify improvement opportunities.

The ERP is treated as a living document, reviewed:

- Prior to each major operational phase
- After drills or exercises
- Following incidents or near-misses
- When significant operational changes occur

Emergency management is closely integrated with the HSE risk-management framework and the Monitoring, Measurement and Verification (MMV) system. Real-time monitoring data and MMV outputs support early detection of abnormal conditions and informed decision-making during emergency situations, particularly those related to well integrity and subsurface behaviour.

6.4 CO_2 source and transport logistics

The transport and injection system is designed for a research-scale pilot involving the delivery and offshore injection of up to 100 kt of CO_2 over an effective operational period of ~15 months, within a broader pilot timeframe of three years. The system is intentionally modular, avoiding fixed infrastructure to minimise upfront capital investment and maximise operational flexibility.

Securing a reliable source of CO_2 is critical for the pilot phase. As CCS remains at an early stage of industrial deployment, emitters interested in small-scale capture solutions are considered as potential sources. Among these, the cement production facility in Souselas represents the primary candidate for sourcing CO_2 for the pilot.

To avoid fixed infrastructure prior to reservoir validation, a flexible and modular CO_2 transport chain is implemented for the pilot. This includes (Figure 28):

1. liquefaction of CO_2 at source;
2. transport from Souselas in cryogenic container tanks by train to the port;
3. at the port, the containers are loaded onto a vessel;
4. transport by vessel to the selected storage site and direct CO_2 injection from the vessel into the reservoir.

Design of the transport chain ensures that all stages of transport are modular and can be rented, re-deployed and/or re-purposed. For the injection pilot, a maximum of 99 kt of CO_2 are considered for transport and injection; this is the crucial design parameter to determine the time, size and cost of the entire transport chain.

6.4.1 From capture to port

The CO_2 stream from the cement plant, initially at low pressure and near-ambient temperature, is captured and conditioned to enhance its purity prior to liquefaction. It is then liquefied to increase its density (to approx. 1070 kg/m^3), by achieving moderate pressure (15 bar) and low temperature (-29 °C). This allows CO_2 storage in cryogenic containers that can maintain the liquid state for extended periods (for several weeks) without the need for re-liquefaction systems along the chain. Each cryogenic container tank has a storage capacity of approximately 23.5 t of CO_2. The containers have safety valves to release pressure in case of emergency and comply with European regulations for the carriage of dangerous goods by rail (RIO), and with the International Maritime Organization (IMO) Class 2.2 standards for non-flammable, non-toxic gases. Their standardized ISO dimensions allow direct loading onto trains and vessels chain, ensuring compatibility across the entire transport chain.

The 55 km one-way rail transit from Souselas to the Port of Figueira da Foz journey is expected to take less than two hours using the existing railway line (Table 22).

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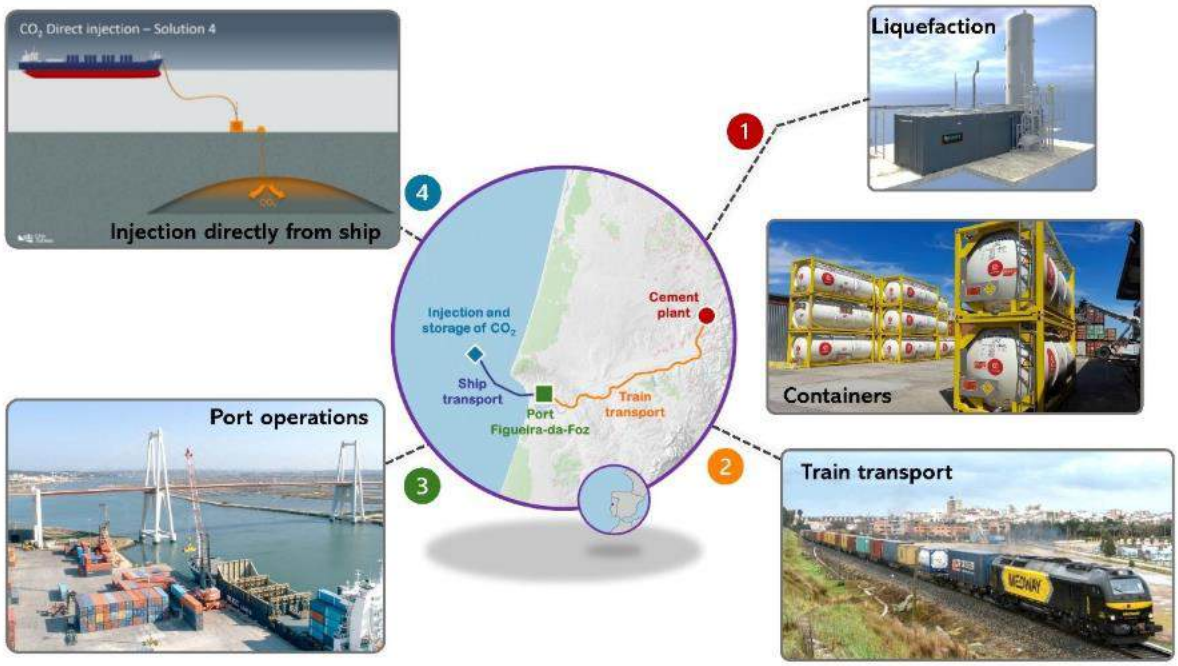

Figure 28 - Operational sequence of transport chain

Parameter	Value
Departure point	CIMPOR Souselas
Arrival point	Port of Figueira-da-Foz
Distance	~55 km
Number of containers per train	~28
Transported CO_2 per train	~650 t

Table 22 - CO2 transport network details for train from Souselas to Figueira da Foz.

The container movement is organized into three operating sets, each comprising 28 cryogenic containers that circulate through sequential stages: (1) loading of CO_2 at the Souselas cement plant, (2) transport of loaded containers to Figueira da Foz, and (3) transfer onboard the ship for injection. Following CO_2 discharge, the emptied container set is swapped with the loaded one and transported back by rail to the capture site, completing a closed-cycle operation that enables continuous transport.

6.4.2 From port to ship

Port operations are designed to ensure efficient transfer of containers between the train and vessel without intermediate storage facilities. Upon arrival at the Port of Figueira da Foz, the empty container

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set returned from the previous offshore injection trip is unloaded, and the full CO_2 containers are loaded onto the offshore supply vessel.

Port handling is based on standard container cranes and/or reach stackers compatible with 20ft ISO containers. At the existing solid bulk terminal, the train park and the ship dock location are separated by around 125 m, with the containers yard being located between them, providing the ideal location for the port operations. The considered handling times for train and ship operations at the port are around 6 hours, where the 28 full containers arriving in the train are swapped for the 28 empty containers from the ship.

6.4.3 Ship transport and direct injection

A dedicated offshore supply vessel is chartered specifically for CO_2 transport and direct injection operations. The reference is based on existing supply vessels such as UT 745 or MT 6000 type, particularly the MT 6000 ROV version. These provide sufficient deck space to install the structural support for the containers and offshore handling equipment. Moreover these ships are able to accommodate control systems and crew quarters adequate for the duration of the operations; in that sense the MT 6000 ROV version may be the most suitable since it is designed to launch and retrieve equipment, is equipped with a dedicated control room and can accommodate larger crews. Selection of the ship must consider dimensions (Table 23) to ensure port compatibility and to provide stability during the injection operations. The current port draft limitation (~6.5 m) represents a critical constraint. Planned dredging to ~8.0 m is assumed in the base case; however, this must be confirmed prior to implementation.

Alternative vessel selection or operational adaptations may be required if this upgrade is not realised and final vessel selection shall be confirmed during FEED, including verification of deck load limits, stability criteria and integration of injection systems.

Parameter	Value
Vessel type	Offshore supply vessel
Length overall	<90 m
Beam	<20 m
Expected draft	<6.5 m
Deck area	>900 m^2

Table 23 - Main characteristics of the reference CO_2 injection vessel

The selected vessel is equipped with dynamic positioning capability to maintain position at the injection site without anchoring, ensuring stable operations above the injection site.

In addition, several dedicated systems are required to ensure safe and efficient offshore injection onboard the ship. These include: (1) CO_2 transfer manifolds and flexible hoses for connection between containers and the injection system, (2) high pressure injection pumps, (3) heat exchangers to recondition the CO_2, (4) a common manifold connection to the injection hose, and (5) safety equipment.

Figure 3-2 depicts the ship-to-well connection system for direct injection of CO_2:

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i. a hose catching system onboard the vessel is used to retrieve and reel in the riser hose, which is then connected to the outlet of the onboard CO_2 reconditioning system;

ii. the riser hose is anchored to a riser bed located on the seafloor;

iii. the riser bed is connected via a jumper pipeline to the subsea Christmas tree (X-tree), which is installed on top of the wellhead;

iv. the X-tree will control the CO_2 flow by handling the injection rate and pressure, and it contains valves, monitoring equipment and allows for a quick shutdown of the well in case of emergency;

v. The control system in the X-tree will connect to the control station on the ship through an umbilical cable that is bundled together with the riser hose.

Since only one well and injection line will be used, a manifold to manage flow collection and distribution is not expected to be needed.

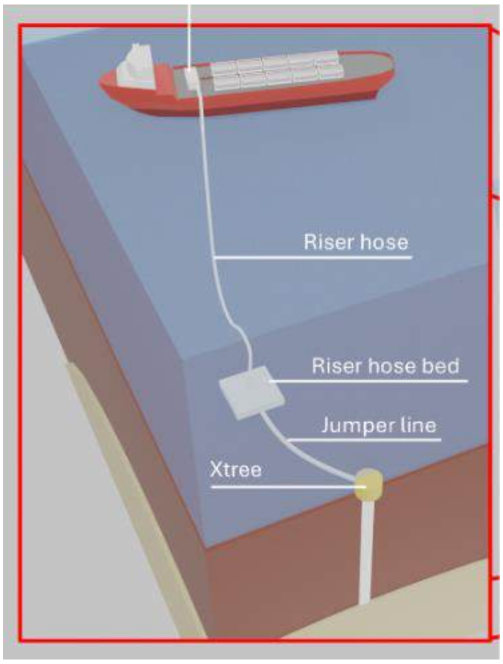

Figure 29 - Detail of the subsea component of the injection process.

The maritime transport and injection characteristics for a single voyage injection cycle are summarised in Table 24.

The onboard reconditioning process is addressed in detail in section 5.4.3 and illustrated in Figure 30 - Simplified diagram of the reconditioning process on the ship, from storage conditions in transport tanks to conditions at the wellhead, but a brief description follows. During injection, the pumps first raise the pressure to the required wellhead injection conditions of approximately 51 bar. A combination of electric and seawater heat exchangers is then used to reach the target temperature of 14 °C. CO_2 enters the wellhead at these conditions and reaches bottomhole conditions (~1120 m depth) at 27 °C and 143 bar, in dense-phase, ensuring that no phase transition occurs along the wellbore. These operating parameters are consistent with the thermodynamic design and ensure stable dense-phase CO_2 injection under all operating conditions.

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Seawater heating can provide the majority of heat to the CO_2 (depending on seawater temperature) while maintaining the heater outlet well above the freezing point of seawater. The remaining heat is supplied by the electric heater. This combination of seawater and electric heating reduces the energy demand and improves operational efficiency.

Parameter	Values
Distance from port to injection site	~22 km
Duration of one-way vessel transit	~3 h
Quantity of CO_2 per trip	~650 t
Maximum injection rate	100 t/h
Preparation time for injection	~4 h
Duration of direct injection	~6.5 h
Wellhead pressure during injection	51 bar
Wellhead temperature during injection	14 °C

Table 24 - Transport and injection characteristics for a single vessel cycle

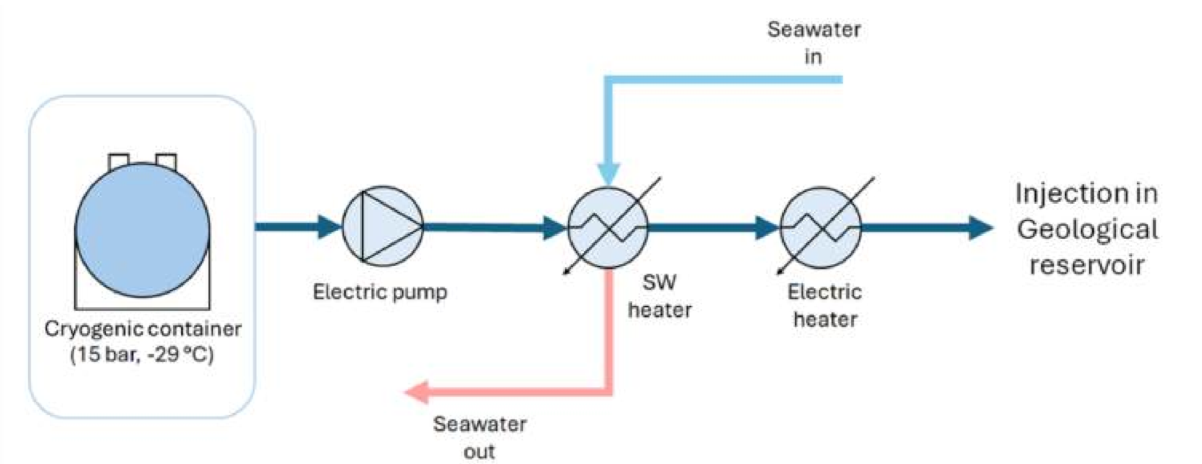

Figure 30 - Simplified diagram of the reconditioning process on the ship, from storage conditions in transport tanks to conditions at the wellhead

The dynamic positioning (DP) system (DP2 class) maintains vessel stability during injection operations, even under moderate environmental loads, ensuring that hose tension and bending remain within allowable limits during injection. Operational limits for maritime injection are primarily defined by metocean conditions, in particular the significant wave height at the injection site. The selected DP2-class vessels are capable of operating with wave heights up to 3 m (depending on wind and current conditions). Based on hindcast data for the period 2010–2025, wave heights above 3 m only occurred 13% of the time at the injection site, while wave heights above 2 m occur with 40% frequency.

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6.4.4 Operational cycle

The operational cycle of the pilot integrates filling of empty tanks at capture site, transport and injection into a single time synchronised chain. The reference daily schedule (Figure 31 - Complete operational cycle schedule of CO2 from emitter to injection site) illustrates the time allocation of activities for both train and ship, including loading and unloading of containers, rail transit, port operations, offshore transit, preparation and direct injection.

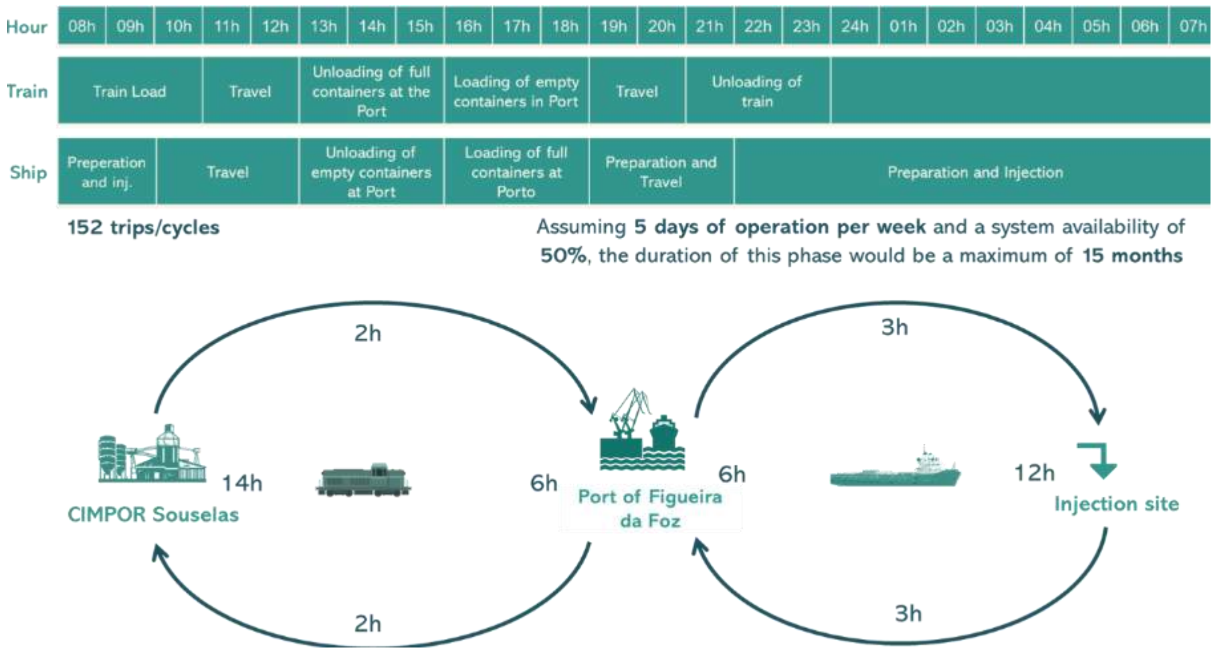

Figure 31 - Complete operational cycle schedule of CO2 from emitter to injection site

Once the cryogenic tanks are loaded onto the ship for transport, preparations for unloading begin. These include maintaining the injection manifold line at the required temperature, connecting discharge hoses, performing equipment testing, and conducting emergency system checks. Injection is carried out in batches to maintain operational control, minimize uncertainties, and allow for trim corrections. This approach provides the crew with sufficient buffer time to perform additional checks and establish connections on non-operating tanks.

Each operational cycle transports approximately 650 t of CO_2, corresponding to 152 cycles required to inject 99 kt of CO_2 into the reservoir. Due to port restrictions and scheduling constraints, operations are limited to five days per week, with each full cycle taking about 24 hours. To account for weather-related downtime, maintenance activities, and other operational uncertainties, an overall system availability of 50 % is assumed. Considering that availability factor, the total duration required for injecting up to 99 kt of CO_2 is estimated to be, at maximum, approximately 15 months.

The overall transport and injection concept is illustrated in Figure 32 - Schematic representation of the CO_2 transport and injection chain for the pilot phase. The detail in the red inset shows ship-to-well connection (not to scale, injection depth is more than 1100 m below sea level)., which shows the complete chain from the CO_2 emitter to offshore CO_2 reservoir.

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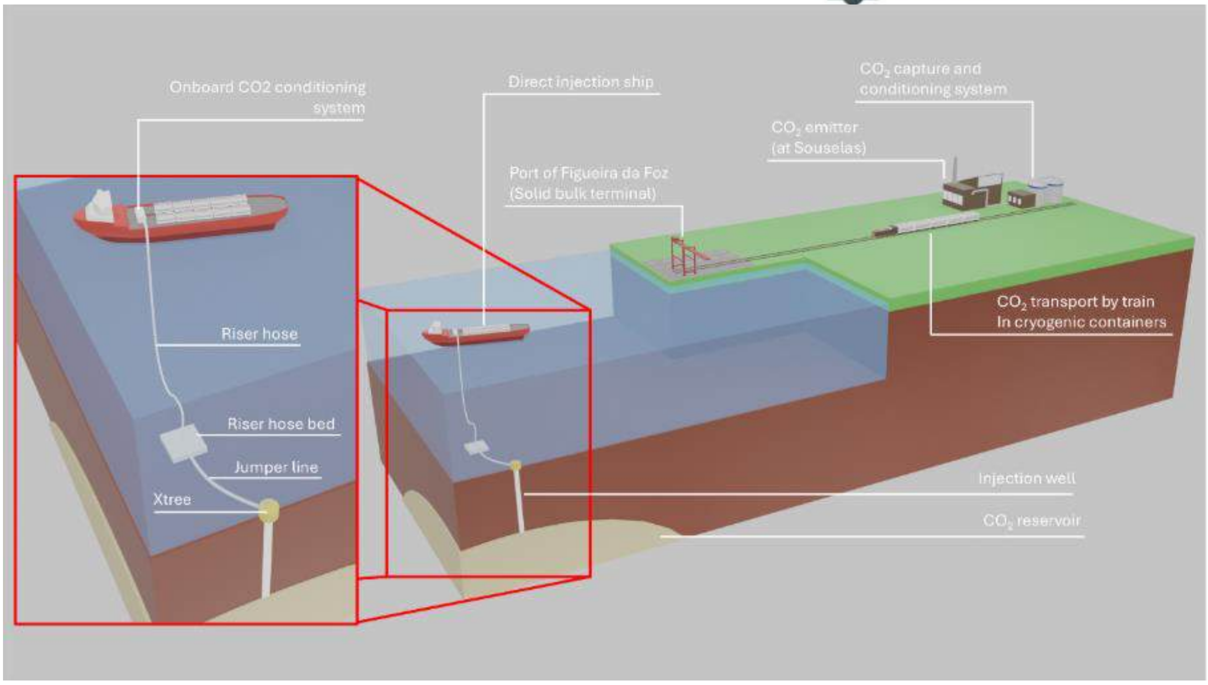

Figure 32 - Schematic representation of the CO_2 transport and injection chain for the pilot phase. The detail in the red inset shows ship-to-well connection (not to scale, injection depth is more than 1100 m below sea level).

6.5 Design of the conditioning processes

The purpose of CO_2 conditioning is to ensure that the captured CO_2 stream is transformed into a stable, transportable and injectable fluid, fully compatible with the transport system, offshore injection infrastructure and reservoir conditions. The conditioning process is designed to:

- ensure thermodynamic stability of CO_2 throughout transport and injection;
- avoid phase transitions that could compromise flow assurance, well integrity or operational safety;
- meet purity and quality requirements for safe handling, transport and injection;
- ensure compatibility with materials, operational procedures and monitoring systems.

The selected operating conditions are defined to maintain CO_2 in a dense phase throughout the chain, ensuring predictable behaviour and minimising operational risks. The design is consistent with the requirements of Directive 2009/31/EC, ensuring that conditioning does not introduce additional risks to containment, transport or injection operations.

The following sections detail the conditioning process at the capture site and onboard the vessel, in accordance with the pressure and temperature conditions requirements presented in Table 3-3, provides recommendations for optimising the design. Annex 2 includes a detailed thermodynamic analysis of the system.

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6.5.1 Conditioning at the capture plant

In a cement plant equipped with post-combustion capture with amines, CO_2 leaves the capture system as a near-pure stream, at low pressure after desorption, and is subsequently compressed and cooled to the conditions required for transport or storage.

CO_2 is released into the head of the desorber at a pressure slightly above atmospheric pressure, typically around 1.8–2 bar absolute. After steam condensation and cooling, the CO_2 gas temperature after steam condensation and cooling is usually in the range of 25–40 °C, with typical purities above 98% by volume prior to compression. Key requirements for the captured CO_2 are low water content, to prevent corrosion and hydrate formation and controlled levels of impurities (e.g. O_2, SOx, NOx), to ensure compatibility with materials and avoid adverse phase behaviour. Where required, dehydration and gas treatment steps are included upstream of liquefaction to ensure compliance with these specifications.

Figure 33 details an industrial process for liquefying and conditioning captured CO_2 for subsequent transport and storage. The main objective is to condition the captured gas (at low pressure and ambient temperature) into a dense liquid at moderate pressure (15 bar) and low temperature (-29 °C) in accordance with the conditions expected for transport in the cryogenic containers (Table 3-3).

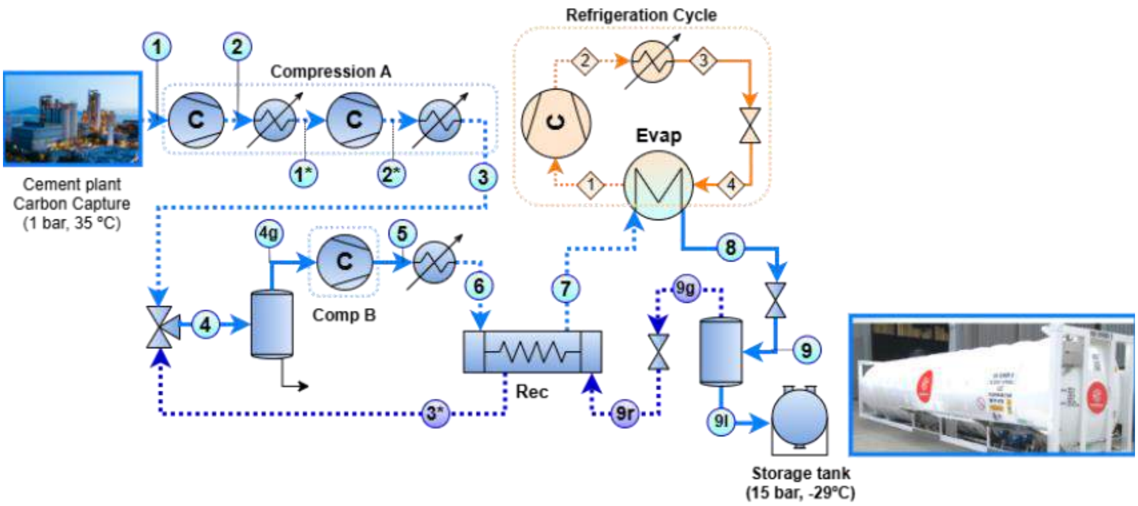

Figure 33 - Simplified diagram of the conditioning process from capture conditions to storage conditions in transport tanks.

The conditioning process includes the following main steps, illustrated in Figure 33:

6.5.1.1 Compression step A

- (1-2*): CO_2 enters the gaseous state under near-atmospheric conditions (1 bar and 35 °C). The gas passes through a series of compressors (C) and heat exchangers (intermediate coolers to 35 °C) to increase its pressure efficiently. With a compression ratio of 15, it is common in standard industrial applications to use two stages of compression. Compression ratio 3.87 per stage (in the range 2.5–4.0 for reciprocating or centrifugal compressors).
- (3): The flow exits this first stage at a significantly higher pressure. The outlet pressure of compression train A is set in a first design stage as the desired transport pressure (15 bar).

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6.5.1.2 Mixer

- (3-4): The gas is mixed with the recirculated gas (3*). If necessary, it would pass through a phase separator, before entering the next compressor stage. Here, liquid impurities or residual water are removed. Under design conditions, this separator would is not expected to be required.

6.5.1.3 Compression step B

- (4g): The gas enters the second compression stage, Comp B (Compression B).
- (5) and (6): After a final stage of compression and cooling, the CO_2 reaches the pressure necessary to start the liquefaction process.
- The design of the second compressor is carried out with a compression ratio equal (3.87) to that of the compressors in the previous step.

6.5.1.4 Cooling

- Rec (Recuperator): At point (6), the gas enters a recuperator heat exchanger. Here it is pre-cooled using the cold streams returning from the end of the process (9r).

Refrigeration Cycle: This is an external system (modular) that acts as a heat sink. Coupled with a heat exchanger to condense CO_2 in its gaseous state. Pre-cooled gas from Rec enters the CO_2 condenser at (7) where it condenses and comes out at saturated liquid (8). The operating conditions of the external compression refrigeration cycle depend on the CO_2 condensation temperature (linked to the outlet pressure of compression train B) and the efficiency of the equipment's heat exchanger. This design assumes a minimum temperature difference in the heat exchanger of 5 °C.

Ammonia (NH_3) has been selected as the main refrigerant for the external cycle. This choice is based on its excellent thermodynamic properties and high heat transfer coefficient in the required temperature range. However, it is recognised that there are alternative fluids that could be evaluated at later stages of the design.

6.5.1.5 Final Separation and Storage

- (9): The flow passes through an expansion valve that reduces the pressure to the level required for transport (15 bar), causing a drastic drop in temperature.
- (9l): The liquid CO_2 is decanted and sent to the transport tank. The final product is stored in cryogenic tanks at 15 bar and -29 °C, standard conditions for the stable and safe transport of liquid CO_2.
- (9g): The CO_2 that remains in the gaseous phase is recirculated.

6. *Secondary expansion*

(9r) The possibility of introducing a secondary expansion to reduce the outlet pressure of compression train A, and consequently that of compression train B, is considered, with the aim of achieving a lower condensation temperature and a reduction in the recirculated mass flow. Different pressure values are analysed in the report. The final transport pressure (15 bar) remains unchanged.

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6.5.1.6 Recirculation

(9r-3*): The recirculated cold gas passes through the recuperator (Rec) to cool the incoming gas (point 6), optimising the energy efficiency of the system before returning to the start of the compression cycle.

6.5.2 Reconditioning on board

Figure 3-7 shows the final stage of the CCS chain: the discharging and reconditioning process for injection in a geological reservoir. Here it is shown how liquid CO_2 is managed once it reaches its destination, with the cryogenic containers being transported by ship to the offshore injection site.

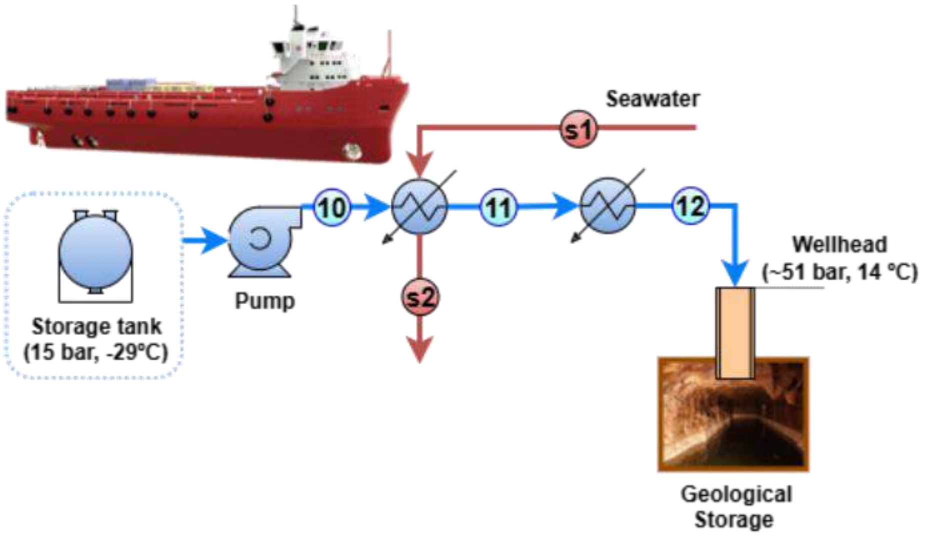

Figure 34 - Simplified diagram of the reconditioning process on the ship, from storage conditions in transport tanks to conditions at the wellhead

The containers selected and the transport train and ship travel time allow for the liquid CO_2, when reaching the injection site, to maintain the initial conditions 15 bar and -29 °C. These conditions are consistent with the transport and injection design basis defined in Section 3.1 (Table 3-3).

The conditioning process includes the following main steps, illustrated in Figure 34:

6.5.2.1 Pumping (Pressure Increase):

The pump takes the liquid CO_2 and increases its pressure. Point (10): The fluid leaves the pump at a significantly higher pressure (51 bar).

6.5.2.2 CO2-Seawater heat exchanger:

To prevent the CO_2 from entering the well at excessively low temperatures and avoid the risk of CO_2 hydrate formation, a heat exchanger is used.

- Seawater (which is at an ambient temperature above -29 °C). The seawater transfers its heat to the CO_2 and is discharged back into the ocean at point (s2). In this preliminary design, it is assumed that the water has a temperature of 15 °C and the exchanger has a minimum temperature difference (dTmin) of 5 °C. In this case, the CO_2 will have an outlet temperature of 10 °C, which makes it necessary to use an additional electric heater.

6.5.2.3 Additional Heater

For cases where the sea water temperature does not allow heating to the desired conditions, an additional electric heater is used. Considering a dTmin=5 °C, the additional heater will be necessary whenever the seawater temperature is below 19 °C.

6.5.2.4 Injection (Wellhead):

Point (12): After heat exchange, the CO_2 reaches injection conditions: ~51 bar and 14 °C. At this pressure and temperature, CO_2 is in a dense or compressed liquid phase. These conditions ensure consistency with the overall system design and operating envelope defined in Section 3.1.

$$COP = {}^{Thermal\ power}/_{Compression\ power} = {}^{7184.89\ kW}/_{582.04\ kW}$$

Flow assurance considerations are explicitly addressed in the conditioning design. The increase in temperature prior to injection prevents hydrate formation and avoids thermal shocks in the wellbore. Pressure and temperature conditions are maintained within the single-phase region of CO_2, ensuring stable flow behaviour during injection.

6.5.3 Design recommendations

Based on the performance evaluation and system sensitivity analysis included in Annex I, the following guidelines are proposed to optimise the technical and economic viability of the process:

6.5.3.1 Compression stage

Selection of the Operating Point: It is recommended to adopt a mixing pressure reduction between 20–40% as the standard design configuration. This scenario achieves significant net power savings. A 30% of pressure reduction is selected as the design point.

Compression Requirements: a greater reduction in condensation pressure results in compressors with lower requirements (compression ratio of 3–3.5, reduced size, and lower cost) while maintaining a similar mass flow due to the reduction in recirculated flow. However, maintaining the condensation temperature above 0 °C (currently ≈0 °C in the 30% case) can prevent the risk of ice or hydrate formation. Note that although both compressors have the same compression ratio, compressor B has higher power requirements due to the increased mass flow rate resulting from gas recirculation.

Operational Flexibility: If compressors with an operating range of 3–3.5 in compression ratio are available, this interval (20–40%) could be covered. This would allow the compression ratio to be increased and the condensation temperature to be maintained above 0 °C (within the range of -9.3 ºC to 6.8 ºC) if operational issues arise.

Safety oversizing. In cases where the ambient temperature is high and air cooling may not be effective, it is recommended to oversize the compressor capacity. Recommendations are based on an outlet temperature of 35°C–50°C for air-cooled heat exchangers.

The proposed control system is shown in Figure 35, including several sensors and control elements, and should be regarded as a proposal.

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Ref	Equipment	Type	Power (kW)	Notes
V-001	FILTER A1	Filter-separator	-	Separator requirement to be confirmed
C-001	COMPRESSOR A1	Compressor	2418	Pressure ratio 3.24
E-001	AIR COOLER A1	Air cooled heat exchanger	2106	Thermal Power
V-002	FILTER A2	Filter-separator	-	Separator requirement to be confirmed
C-002	COMPRESSOR A2	Compressor	2510	Pressure ratio 3.24
E-002	AIR COOLER A2	Air cooled heat exchanger	2673	Thermal Power
V-003	FILTER B	Filter-separator	-	Separator requirement to be confirmed
C-003	COMPRESSOR B	Compressor	2996	Pressure ratio 3.24
E-003	AIR COOLER B	Air cooled heat exchanger	3703	Thermal Power

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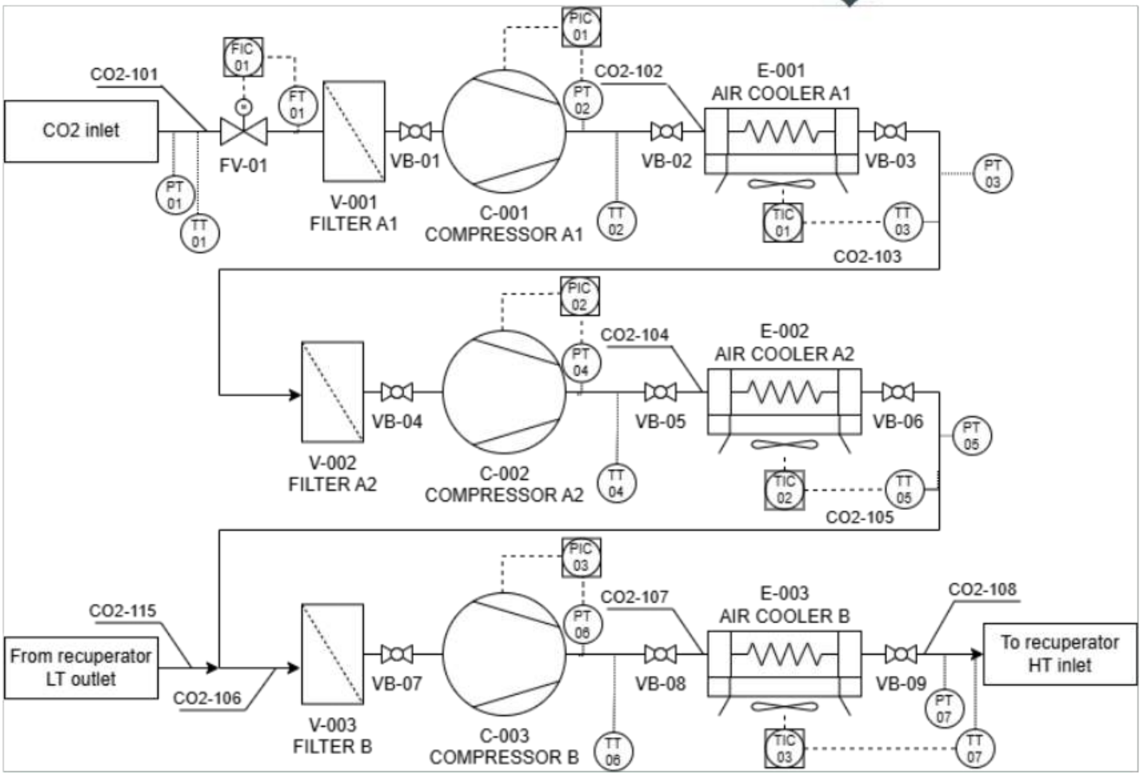

Stream	CO2-10X	1	2	3	4	5	6	7	8	15
Mass flow	ton/h	100	100	100	100	100	123.36	123.36	123.36	23.36
Temperature	ºC	35	132.4	50	151	50	49.2	152.2	50	46
Pressure	bar	1	3.24	3.24	10.5	10.5	10.5	34.02	34.02	10.5
Density	kg/m^3	1.72	4.25	5.37	13.3	17.9	18.0	44.5	64.9	18.2

Figure 35 - Proposed control system for the compression stage. Abbreviations: TT. Temperature transmitter; PT. Pressure transmitter; FT. Flow transmitter; TIC. Temperature Shared display and control; PIC. Pressure Shared display and control; FIT. Flow Shared disp

6.5.3.2 Cooling

Sizing refrigeration cycle (NH3) : Whether opting for a modular solution or a bespoke cycle design, the system must meet the energy requirements (thermal power, mass flow, and condensation temperature) for CO_2 liquefaction (CONDENSER). This must account for the selected operating point.

Ref	Equipment	Type	Power	Notes
E-003	RECUPERATOR	Counter-flow heat exchanger	590.4	Thermal power
E-004	CONDENSER	Heat exchanger with refrigeration cycle	9711.4	Thermal power
PR-001	EXPANDER A	Pressure reductor	-	
S-001	SEPARATOR	Phase separator	-	
PR-002	EXPANDER B	Pressure reductor	-	

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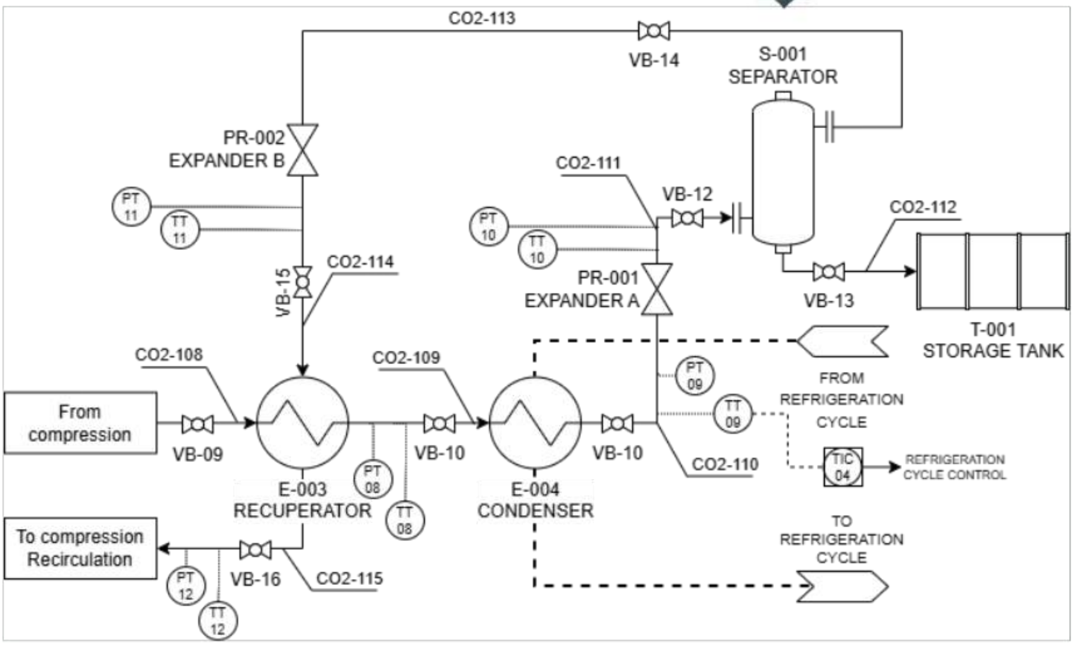

Stream	CO_2-10X	8	9	10	11	12	13	14	15
Mass flow	kg/h	123.36	123.36	123.36	123.36	100	23.36	23.36	23.36
Temperature	ºC	50	35	-0.9	-28.5	-28.5	-28.5	-38.8	46
Pressure	bar	34.02	34.02	34.02	15	15	15	10.5	10.5
Density	kg/m3	64.9	70.5	932.8	178.2	1069.4	39.0	28.2	18.2

Figure 36 - Proposed control system for the cooling stage. Abbreviations: TT. Temperature transmitter; PT. Pressure transmitter; TIC. Temperature Shared display and control; VB. Ball Valve

The proposed control system is shown in Figure 36. It includes several sensors and control elements and should be regarded as a proposal.

6.5.3.3 Reconditioning on board

Prioritising Natural Heat Sinks: Maximize the use of seawater heat exchange within the reconditioning block. The desired conditions should then be ensured using the electrical heater during periods when the water temperature is not sufficiently high.

Sizing: Oversizing the electrical heater's capacity can guarantee the required conditions if the heat transfer surface area is insufficient or when environmental conditions (water temperature) are unfavourable.

Seawater hx dTmin (ºC)	5	10	20
Seawater temp. ºC)	**Thermal power in electrical heater (kWth)**		
10	713.86	1059.6	1698.16
15	337.93	713.86	1385.84
20	0	337.93	1059.64

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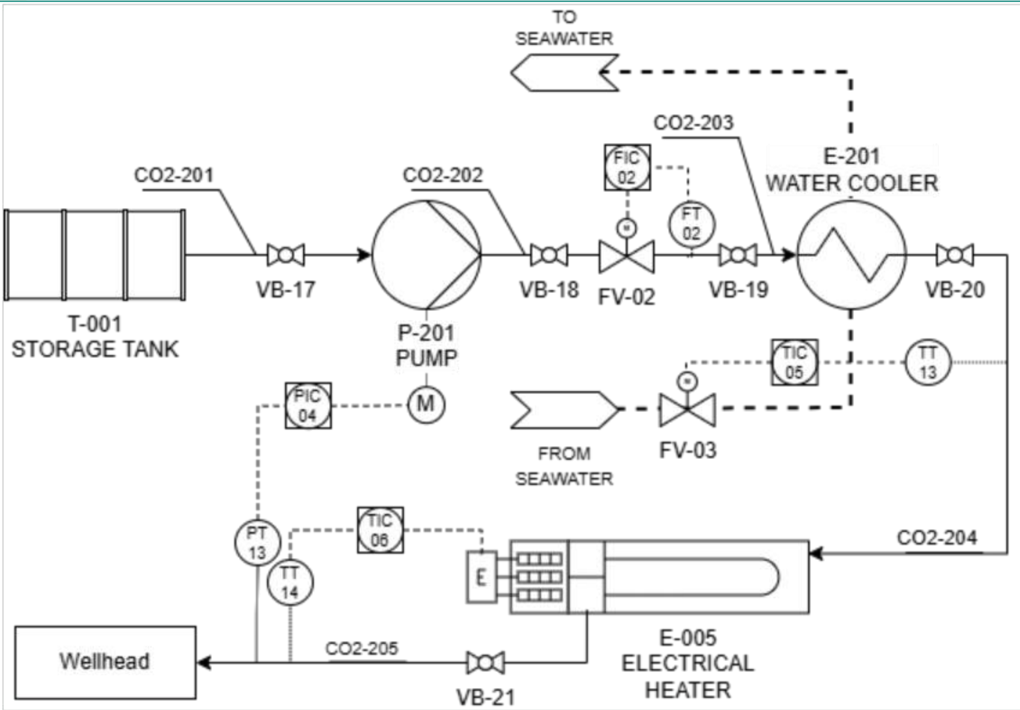
Pumping Safety Margin: The pump must be sized to accommodate potential pressure drops in the subsequent heat exchangers, ensuring that the CO_2 reaches the wellhead at the appropriate pressure conditions.

The proposed control system is shown in Figure 37. The diagram includes several sensors and control elements, which should be regarded as a proposal.

Ref	Equipment	Type	Power	Notes
P-201	PUMP	Centrifugal pump	109	Without pumping safety margin
E-201	WATER COOLER	Water cooler	2675	Thermal power (best-case scenario, without E-005)
E-005	ELECTRICAL HEATER	Electric heater	1700	Thermal power (worst-case scenario)



Stream	CO2-20X	1	2	3	4	5
Mass flow	kg/h	100	100	100	100	100
Temperature	ºC	-28.5	-26.6	-26.6	-10	14
Pressure	bar	15	51	51	51	51
Density	kg/m3	1069.4	1074.2	1074.2	997.3	832.5

Figure 37 - Proposed control system for the reconditioning on board. Abbreviations: TT. Temperature transmitter; PT. Pressure transmitter; FT. Flow transmitter; TIC. Temperature Shared display and control; PIC. Pressure Shared display and control; FIT. Flow Share

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6.6 Qualitative risk assessment of the CO_2 injection pilot

The objective of the risk assessment is to demonstrate that the proposed CO_2 storage pilot in the Lusitanian Basin can be implemented without significant risk to containment integrity, human health or the environment, in accordance with Directive 2009/31/EC and its Guidance Document 1 (GD1). **This assessment, as all other elements in this chapter, is strictly for the pilot phase.**

The qualitative risk assessment builds on the technical risk analysis developed in Deliverable D5.4 (Carneiro et al, 2026), which provides a detailed evaluation of subsurface and operational risks, but expanded to include operational, economic, social, political and regulatory risks that are not addressed in D5.4 but are critical for pilot implementation and permitting.

6.6.1 Methodology

The assessment follows the framework illustrated in Figure 38 in a four-step qualitative process: (i) identification of inherent risks based on updating the Risk Register developed in D5.4; (2) qualitative analysis of those risks; (3) definition of risk response and (4) qualitative reassessment to establish residual risks.

Risks were reviewed based on an updated Risk Register, including the description of the event, possible causes, consequences, category, current mitigation measures and status.

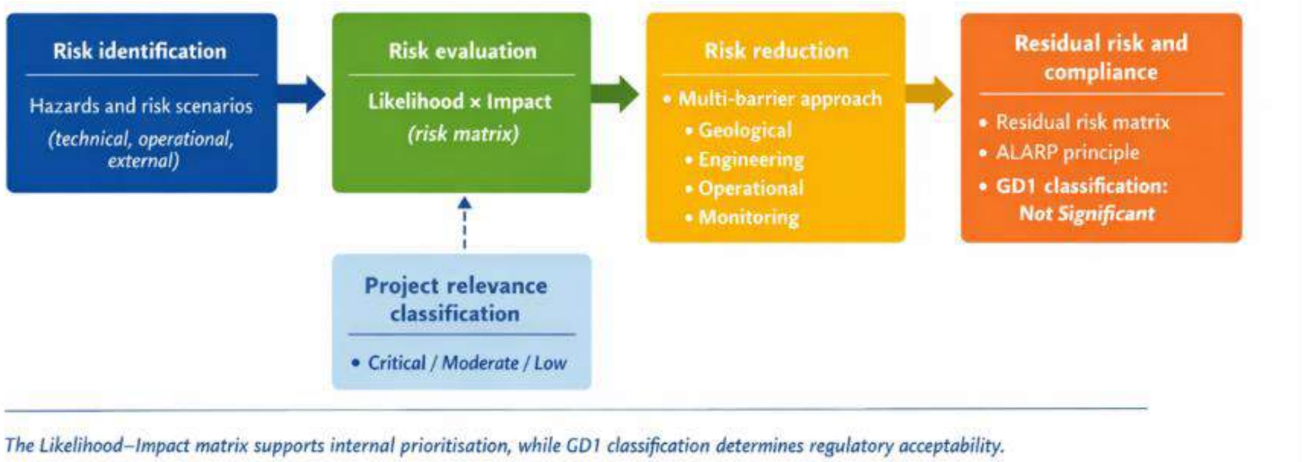

Figure 38 - Qualitative risk assessment framework

Each of these risks identified in the risk register was classified in terms of Likelihood and Impact according to the criteria shown in Table 25, adapted from the proposed REPSOL Projects Risk Management Process. The Likelihood–Impact risk matrix is used for internal prioritisation of risks.

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	Likelihood				
	Very low	**low**	**Medium**	**High**	**Very High**
Event description	Remote chance of happening	May happen less than once during the project lifetime	Expected to occur in the project lifetime	Expected to occur several times in the project lifetime	Occur once or more per year in the project lifetime
Qualitative description	Rare, very unlikely	Unlikely but not impossible	Possible	Moderately likely	Almost certain, will probably arise

	Impact				
	Very low	**low**	**Medium**	**High**	**Very High**
Environment	Fugitive emissions	Controlled release	Emissions exceed limit	Some damage to environment	Widespread damage to environment
Public image	Individual	Local	Regional	Industry-wide	National / international
Qualitative description	Negligible	Minor, easily remedied	Moderate, some objectives affected	Major, most objectives threatened	Most objectives will not be met

Table 25 - Likelihood and Impact qualitative categories (adapted from REPSOL Projects Risk Management Process)

Risks are classified according to the "**Significant / Not significant**" distinction defined in the CCS Directive Guidance Document 1 (GD1), and as applied in D5.4. GD1 advises classifying risks according to their **significance**:

- **Not significant risks**: risks that do not call into question the purpose of the CCS Directive for the storage site concerned; and
- **Significant risks**: risks that must be reduced to *Not significant* by taking risk-reducing measures in order to meet the requirements of the CCS Directive and subsequently achieve compliance with the conditions for transfer of responsibility.

This classification reflects regulatory acceptability, is not directly derived from Likelihood–Impact scores, and results from the potential of each risk to affect containment integrity, environmental protection or regulatory compliance.

6.6.2 Risk identification and evaluation

The revised Risk Register is included in Annex 3 and comprises 49 inherent risks, and covers Containment/Safety, Performance, Operational, Economic/project delivery, Legal/Governance/Policy and Social/Stakeholder dimensions. Figure 39 further organises these risks according to their functional role in the project, distinguishing between technical, operational and external/system-level domains.

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Figure 39 - Structured overview of the risk considered for the Lusitanian Basin CO_2 storage pilot, showing the distribution of identified risks across technical, operational and external/system-level domains. Risk IDs refer to the Risk Register (Annex 3).

The Likelihood and Impact of each risk was established in a HAZID process involving the Portuguese team members, resulting in the inherent risk matrix depicted in Figure 40.

	Impact: Very Low	Low	Medium	High	Very High
Very High	R21	R32	R36		
High			R18	R43	
Medium	R9p, R41	R10p, R19, R20, R30, R37, R39, R49	R31, R46	R23, R24, R42, R44, R45	
Low	R8p, R13, R25	R47	R14, R17, R40	R15	
Very Low	R2p, R5p, R11p, R16, R26, R38	R6p, R7p, R27, R29, R34, R35	R22, R48	R3p, R4p, R12, R28, R33	R1p

Figure 40 - Risk matrix for the CO2 injection pilot project in the Lusitanian Basin

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The inherent risk matrix (Figure 40) shows that:

- no dominant high-risk geological or engineering limitations are identified;
- technical risks are generally low to moderate, reflecting favourable site conditions and conservative design assumptions;
- higher-risk exposures are primarily associated with non-technical factors, particularly permitting, funding and stakeholder acceptance.

This distribution is consistent with the findings of D5.4, which demonstrate that no credible scenario leads to uncontrolled CO_2 release at pilot scale.

The following sections identify the criticality of risks to the project implementation.

6.6.2.1 Critical and non-critical risks to project implementation

Critical risks are those that may affect project implementation or delivery. These risks may be Significant or Not Significant in GD1 terms but are prioritised here based on their potential to affect project implementation. Their importance lies not only in their score in the risk matrix, but also in their capacity to become critical-path constraints for project authorisation and implementation.

The most critical risks are (Table 26):

- **Regulatory and permitting risks**, including delays or uncertainty in administrative procedures;
- **Political and institutional readiness**, affecting project authorisation and continuity;
- **Stakeholder acceptance**, including public perception and maritime-use conflicts;
- **CO_2 supply and funding constraints**, which directly affect project feasibility;
- a limited number of **technical risks linked to containment assurance**, notably plume behaviour and well integrity, which require demonstration during the pilot phase.

These risks are predominantly **external to the storage complex**, confirming that project feasibility is driven more by governance and implementation conditions than by subsurface uncertainty.

Risk ID	Risk description	Comment
R18	Pilot costs higher than estimated	A key implementation risk for pilot continuity and delivery
R23	Public resistance to the project	Can delay implementation, increase scrutiny and affect social licence
R24	Lack of political will to implement the CCS project	Critical enabling condition for project progression and administrative support
R28	Damage to the wellhead, leading to a leak or shutdown	Low-likelihood but high-consequence event requiring strong prevention and response measures

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R33	Infrastructure damage from natural seismicity	Significant due to potential operational consequences even if likelihood is low
R36	Restrictions to fishing activities around the well location	High-likelihood social/maritime-use conflict requiring active management
R42	Lack of financial incentives or changes in CO_2 pricing	External/system-level risk affecting feasibility and continuity
R43	Uncertainty in CO_2 supply sources	One of the strongest implementation risks because the pilot depends on a reliable source stream
R44	Difficulties in access to subsidies / incentives / funding	Major risk to financing and execution
R45	Uncertainty in CCS policy support or unexpected regulatory changes	Can directly affect authorisation and project continuity
R46	Delays or inability to obtain key permits	Critical-path risk for implementation even without high technical severity

Table 26 - Critical risks

Moderate risks correspond to risks of limited impact on project implementation and do not affect regulatory compliance. Moderate risks primarily relate to operational performance, reservoir behaviour and external interactions, and are expected to remain manageable through appropriate mitigation and adaptive operational control. They include:

- **Reservoir and injectivity uncertainties**, such as pressure response variability, localised permeability effects and potential injectivity decline;
- **Monitoring and operational performance risks**, including the effectiveness of monitoring systems and coordination of simultaneous operations;
- **Interactions with other maritime uses**, including potential disturbances to fishing or tourism activities;
- **Societal risks**, notably stakeholder perception and potential localised opposition.

These risks may influence project performance or scheduling but are not expected to compromise storage integrity.

Low risks correspond to well-understood processes with negligible impact on both project implementation and regulatory compliance. Low risks are predominantly associated with containment and subsurface processes, which are inherently constrained by the geological setting and conservative design assumptions. They include:

- **Potential leakage pathways**, such as through wells, caprock or faults, all assessed as highly unlikely under pilot conditions;
- **Geochemical interactions and fluid migration processes**, including CO_2–rock interactions and brine displacement;

- **Secondary operational or environmental effects**, with limited likelihood and negligible impact at pilot scale.

These risks are classified as **Not Significant**, as they do not challenge the integrity of the storage complex or the protection of human health and the environment.

6.6.3 Risk reduction proposal and qualitative re-assessment

A fundamental requirement is in accordance with Directive (2009/31/EC) and its Guidance Document 1 (GD1) for project implementation is that no residual risks remain **Significant** in a manner that would call into question the integrity of the storage complex or the protection of human health and the environment. **In practical terms, this implies that no risks are accepted within the High or Very High zones of the risk matrix after mitigation**. In regulatory terms, this corresponds to all risks being classified as Not Significant under GD1.

Another key principle of risk management in the Guidance Document GD1 (European Commission (2024) is that the level of risk is reduced As Low As Reasonably Practicable (ALARP). This implies that some risks may be assessed as contingent acceptable or tolerable if the cost or effort associated with reducing the risk is disproportionate to the level of risk, and the risk can be maintained at a not significant level.

Risk reduction is achieved through a multi-barrier approach, combining geological, engineering, operational and monitoring barriers. These barriers act as independent layers of protection, both preventively (reducing likelihood) and correctively (limiting impact, ensuring that all risks are reduced to acceptable levels in accordance with GD1 and ALARP principles. Accordingly, mitigation barriers have been defined, falling into four categories:

1. **Design and subsurface-characterisation** barriers are used to reduce containment and performance risk, including conservative well design, CO_2-compatible materials, pressure-management strategies, targeted laboratory testing, refinement of the geological and dynamic models, and acquisition of pilot data to reduce uncertainty;

1. **Operational and monitoring barriers** are used to reduce execution and integrity risk, including advance planning for drilling resources, robust operational procedures, marine safety provisions, well-integrity checks, and implementation of an MMV system able to verify well integrity, pressure behaviour and the absence of unexpected migration.

2. **Project-management and cost-control barriers** are needed to address schedule and budget risks, including contingency budgeting, phased planning and early management of long-lead items.

3. **Institutional and stakeholder barriers** are required to address non-technical risks, including early engagement with public authorities, clarification of the permitting route, communication with fisheries and other maritime users, and alignment with WP6 stakeholder-engagement work.

6.6.3.1 Residual risk profile

Following the implementation of these barriers, the residual risk matrix (Figure 41) shows that:

- no risks remain in the High or Very High categories;

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- all risks initially classified as Significant are reduced to Low or Moderate levels, while remaining classified as Not Significant under GD1;
- the overall risk profile is ALARP-compliant.

Technical risks remain low and well controlled, while the remaining Moderate risks are primarily associated with project performance, economic conditions, and governance, permitting and stakeholder interfaces.

Operational risks remain moderate because they depend partly on external market availability and execution conditions.

The most relevant remaining residual risks are therefore expected to be uncertainty in political and institutional readiness for CCS in Portugal, delays or ambiguity in permitting and administrative coordination, public or stakeholder opposition if communication is insufficiently proactive, and project-cost escalation or funding pressure. These risks are external to the storage complex and require continuous management throughout the project lifecycle. This pattern is fully consistent with the experience in CCS projects around the world, where most remaining risks after mitigation are largely policy, permitting, funding and social-acceptance risks rather than purely subsurface related.

	Impact: Very Low	Low	Medium	High	Very High
Very High					
High	R21				
Medium	R41	R9p, R19, R20, R30, R32, R37, R39, R49	R18, R36	R43	
Low	R8p, R13, R25	R10p, R47	R14, R15, R17, R31, R40, R46	R23, R24, R42, R44, R45	
Very Low	R2p, R5p, R11p, R16, R26, R38	R6p, R7p, R27, R29, R34, R35	R1p, R3p, R4p, R12, R22, R28, R33, R48		

Figure 41 - Risk matrix after responses proposal for the CO2 injection pilot project in the Lusitanian Basin

The assessment demonstrates that all risks are reduced to Not Significant levels in accordance with GD1, confirming regulatory acceptability of the storage site.

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6.6.3.2 Risk-based implications for monitoring and project management

The risk assessment directly informs the design of the MMV plan and project governance framework (Table 27):

i. Technical and containment-related risks require a monitoring programme able to verify well integrity, pressure evolution, injectivity behaviour and absence of unexpected migration. The fit-for-purpose MMV plan is described in section 6.7 of this report. Each identified risk pathway is associated with at least one primary monitoring action.

ii. Operational risks require strengthened planning, effective coordination between drilling and logistics, and contingency capacity for key operations.

iii. Social, political and regulatory risks require a governance response rather than a purely technical one;

iv. Regulatory risks through permitting strategy and authority engagement; stakeholder risks through targeted communication and engagement;

v. cost risks through project management and contingency planning; and

vi. operational uncertainties through adaptive monitoring and defined operational thresholds.

Mitigation measures for these risks should be supported through a stakeholder and institutional engagement plan specifically tied to the Portuguese pilot, including fisheries, other maritime users and regulators (DGEG, DGRM, APA).

Residual risk domain	Primary control mechanism
Containment / injectivity	MMV system (pressure, DAS, seabed monitoring) + operational thresholds
Operational execution	Procedures, planning, contingency capacity
Permitting / regulatory	Permitting strategy + authority engagement
Stakeholder / maritime use	Targeted communication and engagement (WP6)
Economic / funding	Project management, phased implementation, contingency

Table 27 - Residual risk management domains and controls

6.6.4 Risk governance and maturity

The present assessment is grounded in a project-specific Risk Register and detailed technical analysis, but remains subject to refinement as final design parameters, baseline data and permitting conditions are confirmed.

Risk governance is structured around a lifecycle-based update logic. The Risk Register is to be reviewed and, where necessary, updated at key project milestones, including:

- completion of baseline acquisition and site characterisation;
- finalisation of well design and operational procedures;
- start of injection;

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- occurrence of monitoring anomalies or threshold exceedances; and
- post-injection evaluation.

In addition, interim updates may be triggered by significant deviations between observed and modelled behaviour, changes in project scope, or developments in permitting or stakeholder conditions.

As the pilot progresses, the evolution of each risk—from inherent to residual—should be documented, including justification for reclassification and any associated operational or monitoring adjustments. This approach ensures that risk management remains adaptive, traceable and consistent with the iterative nature of a pilot project.

6.6.5 Synthesis

The qualitative risk assessment demonstrates that the pilot satisfies the Directive requirement of no significant risk to containment, human health or the environment. The main technical risks - well integrity, containment, injectivity and monitoring performance - are typical of pilot CCS projects and can be managed through conservative design, appropriate testing and a robust risk-based monitoring plan. The barrier-based approach is consistent with the risk management framework defined in Guidance Document 1 of Directive 2009/31/EC, which requires demonstration that all risks are controlled through appropriate preventive and corrective measures.

However, its feasibility is strongly conditioned by non-technical project factors. The risks most likely to remain material after mitigation are those linked to policy support, permitting, stakeholder confidence and project funding.

Therefore, the Lusitanian basin pilot project should not be regarded solely as a subsurface-risk issue, but rather as a pilot whose feasibility depends on the successful integration of engineering, monitoring, regulation and stakeholder engagement.

Overall, the inherent risk profile does not identify any dominant geological or engineering limitation. Instead, it shows technical risks are relatively well constrained, while non-technical risks may represent the main drivers of project feasibility and timing.

6.7 MMV Plan

The MMV strategy is structured according to a risk-based, adaptive, and multi-layered monitoring framework, consistent with Directive 2009/31/EC, Decree-Law 60/2012 and internationally recognised guidance including ISO 27914. Its purpose is to demonstrate, throughout the **pilot lifecycle**, the containment of CO_2 within the storage complex, the conformance between observed and modelled reservoir behaviour, and the absence of measurable adverse effects on the marine environment. These objectives are addressed through a combination of complementary monitoring techniques across all relevant domains, with sufficient sensitivity, spatial coverage and temporal resolution to ensure early detection and reliable interpretation of any deviation from expected system behaviour.

The monitoring system is designed to meet the specific requirements of the pilot phase, while the underlying approach remains scalable to a future commercial phase, acknowledging that adaptations may be required as knowledge of storage-complex behaviour improves during the pilot.

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The monitoring intensity and spatial coverage are proportional to identified hazards, potential exposure pathways, and the scale of injection operations, as described in the previous sections on risk assessment. The monitoring programme is organised into three temporal stages:

i. pre-injection baseline acquisition (2029);

ii. operational monitoring during injection (2031-2032);

iii. post-injection monitoring during the pilot duration (2032-2033).

A fourth stage, related to post-closure monitoring, applies to the non-research and demonstration stage, if and when the pilot is scaled up to a commercial CO2 storage site. Likewise, operational monitoring during injection and post-injection monitoring would also extend throughout the commercial project lifecycle. However, the MMV plan described hereafter applies exclusively to the pilot phase.

The overall architecture of the MMV follows a vertical monitoring concept spanning the reservoir, overburden, well system, seabed and water column. Monitoring data are assimilated into the dynamic reservoir model to reduce uncertainty and enhance predictive capability, while model outputs are subsequently used to update the monitoring strategy and procedures optimizing monitoring design. This iterative process ensures that monitoring remains adaptive rather than static, evolving in response to observed system behaviour. The monitoring domains and lifecycle logic are illustrated in Figure 42.

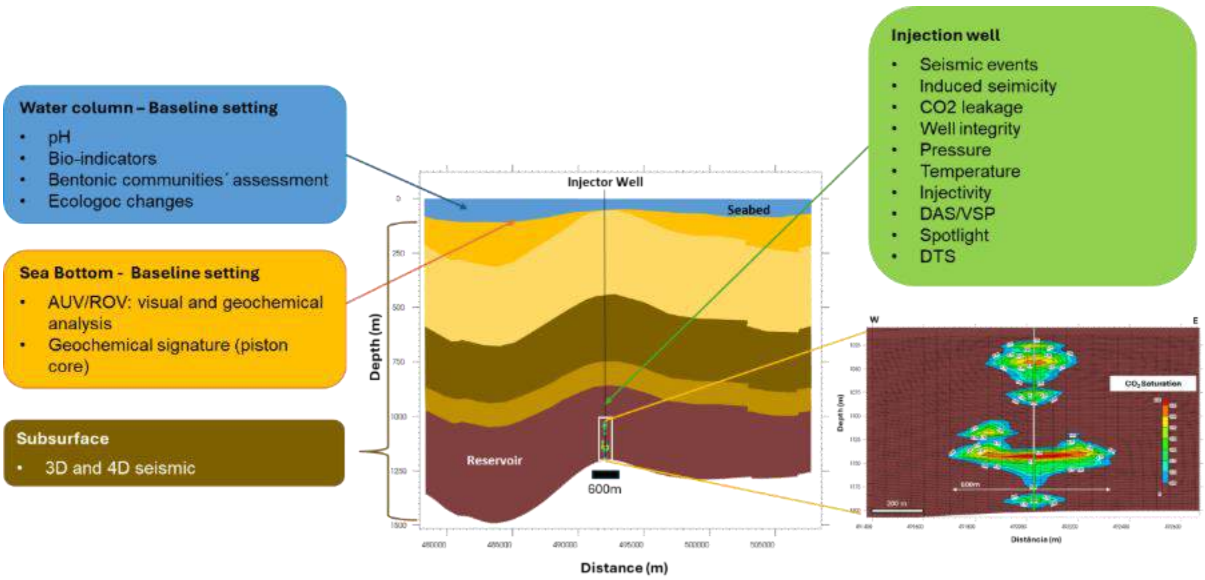

Figure 42 - Illustration of the Monitoring Domains

6.7.1 Monitoring architecture

The designed MMV configuration combines (Figure 43):

i. baseline high-resolution XHR 3D seismic acquisition;

ii. continuous well-based monitoring by means of DAS (Distributed Acoustic Sensing) and downhole pressure/temperature measurements;

iii. periodic well integrity logging;

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iv. seabed monitoring integrating MBES (Multibeam Echosounder) bathymetry;

v. sediment and porewater geochemistry and BACI/Beyond-BACI biological surveys[5];

vi. deployment of a multi-point seabed sensing array of the SpotLight™ type to monitor plume development, and,

vii. water-column monitoring.

Unlike surface-heavy, seismic-dominant approaches, this configuration distributes monitoring sensitivity across several domains of the storage complex - subsurface reservoir, wellbore, seabed interface and overlying water column - providing redundancy and cross-validation of observations.

In this architecture, continuous DAS and pressure monitoring provide real-time conformance assessment and early deviation detection near the well. The addition of SpotLight-type monitoring improves plume detection capability without requiring excessively frequent 4D campaigns, thereby increasing confidence in plume behaviour and potential leakage screening. Environmental monitoring remains proportionate to the limited scale of the pilot: seabed and water-column surveys function primarily as safeguard layers, with monitoring intensity increasing under defined anomaly conditions.

The selection of monitoring technologies, their spatial deployment and their temporal frequency are derived from the site-specific risk assessment (see D5.4 (Carneiro et al., 2026), and section 6.6 above for details) and the identification of potential migration pathways. This ensures that each relevant risk scenario is associated with at least one primary monitoring method and, where appropriate, an independent secondary line of evidence. In this way, the monitoring architecture provides traceability between identified risks, monitoring controls and decision-making criteria, in line with the risk-based approach required by the Directive.

Overall, the architecture aims to achieve technical robustness through multi-scale redundancy, regulatory defensibility through independent lines of evidence, proportionality to pilot injection volume, scalability to future commercial deployment, and cost control relative to more intensive full-lifecycle 4D-dominated programmes.

6.7.2 Baseline acquisition

The baseline programme establishes the operational reference framework for all subsequent monitoring activities. It establishes quantitative thresholds, spatial coverage limits, and measurement precision requirements that will ensure anomaly detection and model validation throughout the project lifecycle. All subsequent monitoring results are interpreted relative to this baseline so that observed changes can be robustly attributed either to project activities or to natural variability.

Baseline characterisation of the storage reservoir is performed through high-resolution 3D seismic acquisition, covering approximately 1,225 km² (35 × 35 km) around the injection site (Figure 44). This dataset will image the structural closure, adjacent fault systems and expected pressure propagation domain. This survey establishes the time-zero reference for future timelapse 4D seismic monitoring.

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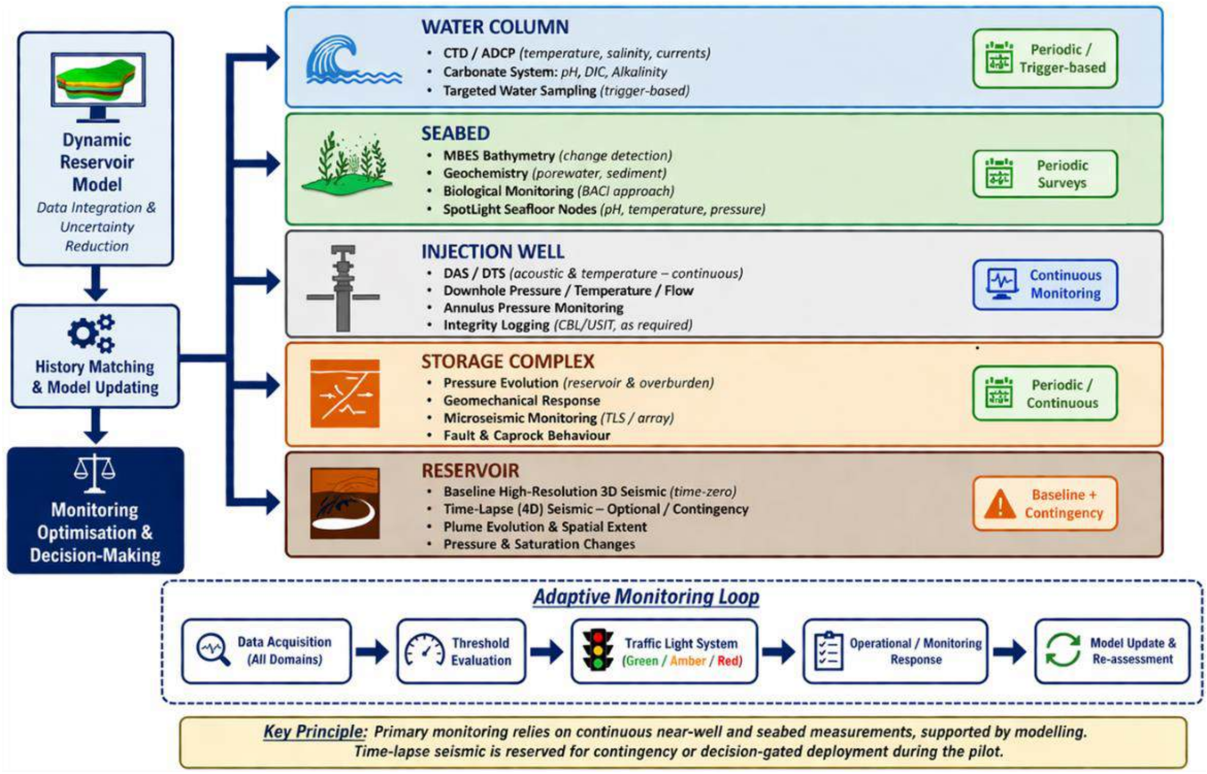

Figure 43 - Integrated MMV architecture for the Lusitanian basin pilot

Considering the 50–180 m water depths and the need for cost efficiency, repeatability, environmental compatibility, and adequate resolution for the 800–1400 m TVDSS target, Extended High Resolution (XHR) ministreamer acquisition is selected as the primary method for time-zero and timelapse monitoring. The mini-streamer configuration (6–12 streamers, 600–1000 m length, 25–50 m separation, high fold acquisition) ensures adequate spatial sampling and repeatability for future time-lapse comparisons.

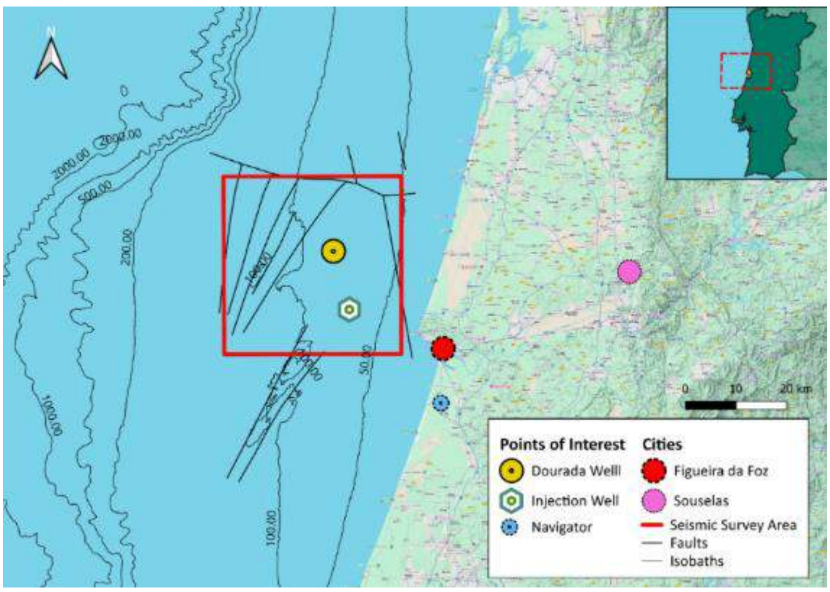

Figure 44 - Seismic Baseline Survey Area with the location of the Dourada-1C legacy well and the proposed CO2 injection well.

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A baseline microseismic network is to be deployed to characterise the active seismicity of the region more robustly and as a complement to the characterisation presented in D2.5 (Olaiz *et al.*, 2024). This can be achieved by reinstalling the PilotSTRATEGY seismic network at Serra da Boa Viagem, which operated from 2023 to 2024, and complementing it with Ocean Bottom Seismometers (OBS), so as to refine epicentral location and improve the accuracy of the magnitude determination down to values below $M_L<0.5$. This baseline supports the definition of background seismicity levels, calibration of the Traffic Light System recommended in D5.4 (Carneiro et al., 2026), and discrimination between natural and potentially induced events during operations.

A robust offshore CO_2 storage monitoring programme requires a spatially resolved seafloor baseline capturing habitat distribution, ecological sensitivity and natural variability. This baseline is established through an integrated approach combining physical seabed characterisation, sediment and porewater geochemistry, and biological community assessment, implemented under a BACI/Beyond-BACI design with stratified Impact and Control stations (Table 28).

Component	Methods	Key Outputs	Monitoring Objective
Physical seabed (MBES)	Vessel/AUV multibeam surveys + water-column backscatter	Bathymetry, backscatter, DTM, geomorphology, acoustic flares	Detect morphological changes and screen for fluid escape
Sediment & pore water geochemistry	Stratified sampling (Impact vs Control)	pH, DIC, alkalinity, Eh, O_2 penetration, TOC, pigments, tracers	Early detection of leakage via carbonate system perturbations
Biological communities	Macrofauna (primary), meiofauna, microbial indicators	Community structure, habitat condition	Detect disturbance and quantify recovery trajectories

Table 28 - Components of seabed baseline acquisition and monitoring.

High-resolution seabed mapping will be conducted using Multibeam Echosounder (MBES) systems deployed from a survey vessel and/or AUV (Autonomous Underwater Vehicles) platform. MBES data define seabed morphology and sedimentary facies, identify pre-existing features, and establish a georeferenced Digital Terrain Model (time-zero surface) against which changes are assessed through repeat-survey differencing. Water-column backscatter further enables screening for acoustic flares associated with gas bubbles. In parallel, geochemical sampling, stratified by habitat and with greater density in the drilling / injection zone, targets carbonate system parameters, where early leakage would be expected to manifest as decreases in pH and increases in dissolved inorganic carbon prior to any morphological or biological response. Biological baseline characterisation focuses on benthic macrofauna and habitat structure, complemented where relevant by meiofauna and microbial indicators, with surveys conducted pre-injection, during high-risk operational windows (drilling and post-drilling), and over recovery timescales extending to ≥24 months in low-resilience sediments. Given the limited scale of the pilot, seabed monitoring is not to be deployed continuously, and is based on a robust pre-injection baseline, trigger-based seabed surveys linked to subsurface anomalies, and an end-of-injection verification survey combining MBES with targeted geochemical and biological sampling to confirm that conditions remain within statistically defined baseline variability.

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Baseline water-column characterisation is required to capture seasonal and vertical variability in hydrographic and chemical conditions. Seasonal Conductivity–Temperature–Depth (CTD) and Acoustic Doppler Current Profiler (ADCP) surveys are proposed to define temperature, salinity, turbidity, dissolved oxygen and density stratification, thereby constraining the mixing regime and bottom-water renewal conditions of the site. These data are to be integrated with available oceanographic datasets to characterise seasonal variability in bottom-water renewal and to identify zones of potential stagnation or enhanced flushing. In addition, baseline carbonate-system measurements include pH, pCO_2, dissolved inorganic carbon and total alkalinity. Where justified, discrete samples may also be analysed for δ^{13}C-DIC in order to strengthen source-attribution capability.

Baseline characterisation of the injection well is to be conducted at a later stage than for the previous environments, to establish reference conditions for integrity and operational monitoring. Distributed Acoustic Sensing (DAS) will be permanently installed along the cemented injection well using single-mode fibre-optic cable integrated in the completion, providing metre-scale continuous acoustic measurements along the wellbore. The optic fibre operates by analysing Rayleigh backscatter generated when coherent laser pulses caused by external perturbations (e.g., flow, pressure, strain, microseismicity) induce changes in the signal.

DAS offers several critical monitoring functions that go beyond the baseline itself:

- Microseismic detection: DAS enables identification of low-magnitude induced seismic events along or near the wellbore, supporting early detection of potential fault reactivation.
- Near-wellbore plume tracking: Variations in acoustic response and strain patterns can indicate CO_2 saturation, phase changes, or preferential flow zones within the injection interval.
- Geomechanical response: Continuous acoustic data can detect fracture initiation, fracture propagation, or stress redistribution associated with pressure build-up.
- Well integrity: Anomalous acoustic signatures may reveal unintended fluid migration behind casing, tubing vibrations, or loss of zonal isolation.

Unlike periodic surface seismic surveys, which provide high spatial coverage but limited temporal resolution, DAS delivers continuous real-time data throughout pre-injection, injection, and post-injection phases. This high-frequency temporal sampling enhances early anomaly detection capability and allows rapid operational response, such as injection rate adjustment or pressure management.

Well monitoring also include installation of permanent downhole instrumentation, namely pressure and temperature gauges, annulus monitoring, together with baseline integrity logging through Cement Bond Log (CBL), Ultrasonic Imaging Tool (USIT) and, where appropriate, calliper logging. These measurements define the initial state of cement integrity, zonal isolation and wellbore geometry, and provide the reference dataset for comparison with end-of-injection and closure integrity verification.

6.7.3 Monitoring programme by project phase

A phase-based structuring of the MMV was adopted in order to ensure that monitoring technologies, monitored parameters and monitoring frequency remains proportionate to the level of risk and uncertainty at each stage of the project, while maintaining continuity between baseline characterisation, operational verification and post-injection confirmation (

Monitoring Domain / Method	Baseline (2027-2030)	Injection (2031-2032)	Post-injection (2032-2033)
Seismic (Reservoir-scale)	High-resolution 3D seismic (time-zero)		Optional 4D seismic (decision-gated)
DAS / Downhole P–T–Q	Installation and baseline acquisition	Continuous real-time monitoring	Continuous real-time monitoring
SpotLight seabed nodes	Installation and baseline acquisition	Continuous plume tracking and anomaly detection	Continuous plume tracking and anomaly detection
Seabed (MBES + geochemistry + biology)	Baseline mapping and BACI surveys	Periodic surveys and trigger-based campaigns	Verification surveys and recovery assessment
Water column (CTD, ADCP, carbonate system)	Baseline hydrographic, and chemical characterisation	Targeted and trigger-based monitoring	Final verification (Before–Occurrence–After)
Modelling, Data Integration & Decision Support	Static model calibration and uncertainty reduction	History matching, model updating and conformance assessment	Model validation long-term behaviour assessment

Figure 45).

Monitoring Domain / Method	Baseline (2027-2030)	Injection (2031-2032)	Post-injection (2032-2033)
Seismic (Reservoir-scale)	High-resolution 3D seismic (time-zero)		Optional 4D seismic (decision-gated)
DAS / Downhole P–T–Q	Installation and baseline acquisition	Continuous real-time monitoring	Continuous real-time monitoring
SpotLight seabed nodes	Installation and baseline acquisition	Continuous plume tracking and anomaly detection	Continuous plume tracking and anomaly detection
Seabed (MBES + geochemistry + biology)	Baseline mapping and BACI surveys	Periodic surveys and trigger-based campaigns	Verification surveys and recovery assessment
Water column (CTD, ADCP, carbonate system)	Baseline hydrographic, and chemical characterisation	Targeted and trigger-based monitoring	Final verification (Before–Occurrence–After)
Modelling, Data Integration & Decision Support	Static model calibration and uncertainty reduction	History matching, model updating and conformance assessment	Model validation long-term behaviour assessment

Figure 45 - Monitoring technologies across lifecycle phases

6.7.3.1 Baseline program

The baseline phase establishes pre-injection reference conditions across all monitoring domains as described in Section 6.7.2. The activities implemented during this phase include seismic acquisition, deployment of monitoring systems, well instrumentation and integrity logging, and environmental baseline surveys. These activities are executed in an integrated manner to ensure spatial and temporal consistency of the baseline dataset prior to injection. The monitoring techniques to be applied in this stage were described in the previous section.

6.7.3.2 Injection phase monitoring

During injection, continuous well-based monitoring provides real-time conformance verification, complemented by SpotLight and environmental safeguard surveys.

- **Continuous injector monitoring:** P/T/Q + annulus monitoring with operational alarms.
- **DAS O&M:** Continuous operation for microseismicity and near-wellbore geomechanical response.
- **Topside O&M:** Continuous operation of wellhead CO_2 detectors.

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- **SpotLight** for plume tracking.
- **Seabed Morphology:** Annual MBES bathymetry surveys.
- **Water Column:** Seasonal CTD and ADCP and carbonate system monitoring.
- **CO_2 stream composition:** Periodic checks (e.g., 3 campaigns/year) during injection.
- **Contingency (Occurrence-based):** Provision for targeted AUV/ROV investigations, intensified geochemistry, or tracer injection if triggered by predefined thresholds (e.g., persistent acoustic flares or pressure deviations).

6.7.3.3 Post -injection monitoring

Post injection monitoring is intended to consolidate evidence of containment and culminates with final well integrity verification before handover for possible commercial project.

- 4D Seismic: A time-lapse (4D) repeat survey may be conducted as a contingency or decision-gated activity, rather than as a routine monitoring requirement. Its deployment will depend on observed behaviour, detectability conditions and the need for reservoir-scale plume confirmation.
- SpotLight for plume tracking
- Well integrity: Final CBL/USIT campaign per injector at the end of closure.
- Seabed Morphology: Final MBES bathymetry mapping.
- Environmental Verification: Final integrated campaign (geochemistry and biological surveys).
- Water Column: Final verification profiling (Before–Occurrence–After strategy).
- Continuous Monitoring: DAS, P/T/Q, and wellhead detectors remain operational until final plug and abandonment (O&M continues).

6.7.4 Monitoring of the storage reservoir and storage complex

The storage reservoir is the primary compartment for demonstrating plume evolution and pressure behaviour. In the Lusitanian Basin pilot, reservoir monitoring relies primarily on baseline XHR mini-streamer 3D seismic selected as the main reservoir-scale technique. The planned survey area of approximately 1,225 km² is intended to encompass the structural closure, nearby faults and the expected pressure-propagation domain. This provides the time-zero reference for subsequent 4D interpretation and plume-conformance assessment.

The monitoring strategy also includes a *SpotLight*-type seabed system and continuous downhole pressure / temperature monitoring, together with DAS / DTS in the injector. This integrated architecture provides two independent lines of evidence: spatially distributed reservoir imaging at campaign scale, and high-frequency monitoring of near-wellbore evolution in real time.

While baseline 3D seismic acquisition is required to fully characterise reservoir geometry, sealing architecture and the pressure-propagation domain, the use of routine time-lapse (4D) surface seismic as a primary plume-tracking method during the pilot phase is disproportionate to the scale and duration of injection. The pilot involves a total injected mass below 100 ktCO_2 over a relatively short

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injection period (approximately 12–15 months), which limits both the expected plume extent and the temporal evolution observable through surface seismic methods.

For this reason, plume behaviour and conformance during the pilot are primarily monitored through continuous downhole pressure and temperature measurements, DAS/DTS-based near-well monitoring, and SpotLight-type seabed monitoring, supported by iterative history matching of the dynamic reservoir model. These methods provide higher temporal resolution and are better suited to detecting early deviations from expected behaviour at pilot scale.

Time-lapse seismic acquisition is therefore retained as an optional or contingency monitoring measure, to be deployed only if required to resolve model mismatch, support scale-up decisions, or provide reservoir-scale spatial confirmation of plume extent. Monitoring of the storage complex addresses the interval above the reservoir, including caprock behaviour, fault-reactivation / induced seismicity, pressure dissipation, and any migration pathways that might compromise containment. This is addressed through continuous pressure monitoring, geomechanical interpretation using DAS, microseismic monitoring, and comparison of observed behaviour against dynamic reservoir and geomechanical models. A central operational threshold is a sustained reservoir-pressure deviation greater than +15% relative to forecast values. Exceedance of this threshold triggers operational response, including reduction of injection rate, revision of the pressure-management strategy, updating of the dynamic model, and reassessment of fault stability.

The MMV plan includes a Traffic Light System for induced seismicity, based on magnitude, Gutenberg–Richter b-value, and peak ground acceleration. Final operational thresholds should be agreed with the competent authority prior to any future commercial-scale permitting step. Observed deviations between monitored and modelled behaviour are used to update the dynamic reservoir and geomechanical models, ensuring continuous refinement of predictive capability. Where necessary, such updates may lead to adjustments in monitoring strategy, monitoring frequency or operational parameters, thereby maintaining alignment between monitoring results, model predictions and risk assessment throughout the project lifecycle.

Monitoring of the injection well and well integrity monitoring includes wellhead pressure, temperature and flow-rate measurements, annulus-pressure surveillance, and permanent downhole pressure and temperature gauges. These are complemented by DAS / DTS fibre-optic monitoring, which provides continuous acoustic and temperature observations along the wellbore. Together, these systems support operational control, early diagnosis of injectivity decline, detection of abnormal thermal or acoustic signatures, and verification of zonal-isolation performance. Well integrity verification is provided by through-tubing CBL / USIT and related logging during baseline and again at the end of operations, with the possibility of an additional mid-cycle campaign if operational evidence warrants it. An annulus-pressure anomaly, sustained DTS temperature deviation, or any indication of cement-integrity concern should result in operational suspension, integrity testing, and remedial intervention if necessary.

6.7.5 Monitoring of the seabed and water column

Seabed and water-column monitoring constitute the final environmental verification layer of the MMV architecture. Their purpose is to provide independent confirmation that no measurable perturbation associated with project activities is occurring at the marine interface.

At the seabed, the monitoring system combines MBES bathymetry, sediment and porewater geochemistry, and habitat-stratified biological surveys under BACI / Beyond-BACI logic. MBES provides the time-zero morphology against which later surveys can identify new pockmarks, seabed deformation or persistent acoustic flares. Sediment and porewater monitoring are designed to detect changes in pH, dissolved inorganic carbon, alkalinity, redox conditions and related carbonate-system parameters, while the biological component is intended to identify departures from baseline benthic community structure or recovery trajectories after disturbance. These techniques are not applied continuously but are repeated at defined phases for comparison with the baseline and intensified if subsurface or geochemical anomalies are detected.

In the water column, the MMV plan adopts a proportionate Before–Occurrence–After approach, based on CTD and ADCP profiling and targeted measurements of pH, pCO_2, dissolved inorganic carbon, alkalinity and dissolved oxygen, again at defined intervals for comparison with the baseline , while accounting for natural hydrographic and seasonal carbonate variability of the site. The water-column layer is therefore confirmatory and trigger-based rather than continuous.

During disturbance activities such as drilling, and if required during injection, water-column monitoring is implemented in a targeted and non-continuous way, including additional CTD and ADCP measurements close to operational areas, focused near-bottom carbonate chemistry sampling and deployment of mobile platforms when triggered by anomalies detected in deeper MMV layers. Monitoring intensity is increased only in response to non-conformance indicators arising from the reservoir, storage-complex or well-monitoring layers, leading to temporary increases in sampling frequency and spatial coverage. Following drilling and again at the end of injection, confirmation surveys are used to verify that hydrographic conditions and carbonate chemistry remain within the range of baseline variability and that no sustained perturbation attributable to project activities is present.

6.7.6 Integration, planning logic and survey frequency

The MMV planning logic is linked to the project modelling outputs, but during injection, continuous well-based monitoring should be maintained, and periodic campaigns are performed at the highest frequency. In the post-injection phase, the frequency of periodic surveys can decrease, if conformance is demonstrated and no anomalies are observed.

This phased reduction in monitoring frequency follows the proportionality of the MMV plan. The highest intensity of monitoring is maintained where uncertainty and operational risk are greatest, namely around drilling, the onset of injection, the injection period itself and the early post-injection period. Where system behaviour remains within forecast ranges and environmental indicators remain within baseline variability, the programme can progressively shift from higher-frequency confirmation to lower-frequency verification.

6.7.6.1 Risks, thresholds and Mitigation measures

Operational and monitoring responses are triggered by predefined thresholds to support adaptive risk management and ensure containment integrity throughout the pilot phase.

- Reservoir pressure: Sustained deviation > +15% relative to forecasted model values should lead to reduction of injection rate, revision of pressure management strategy, updating dynamic model and reassessing fault stability.

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- Injectivity decline: Sustained reduction beyond expected performance envelope should trigger diagnostic well testing and adjustment of operational parameters.
- Microseismicity (DAS monitoring) Traffic light system: A Traffic Light System is proposed in D5.4 (Carneiro et al., 2026) as a decision-making approach to mitigate the risk of potential seismic events induced by CO_2 injection. Traffic Light Systems are based on a decision variable (earthquake magnitude, peak ground velocity, etc.) and a threshold value above which actions (e.g., stopping the injection or reducing production rates) must be taken. As an example, Table 29 shows a possible TLS that rely on event magnitude, the Gutenberg–Richter *b*-value, and/or the peak ground acceleration (PGA) as complementary indicators. This approach enables near-automatic operational decisions, provided continuous local monitoring and rapid data processing are in place, and avoids reliance on magnitude alone by incorporating both early-warning (b-value) and impact-related (PGA) metrics.

The magnitude and ground motion thresholds proposed for the Traffic Light System (TLS) constitute a project-specific operational risk management tool. They reflect international best practice and are suggested as a precautionary operational control mechanism consistent with the risk management principles of Directive 2009/31/EC. Final TLS operational thresholds would be defined in agreement with the competent authority as part of any future commercial-scale permitting process.

Seismic event magnitude	Action	Comment
M <1.5, *b*-value high or stable and PGA negligible	Go	Injection proceeds as planned
1.5 > M < 2.5, decrease in *b*-value and/or moderate PGA	Caution	Injection proceeds with caution, possibly at reduced rates. Monitoring is intensified
M > 2.5, abrupt drop in b-value and/or PGA exceeding conservative ground-motion limits	Stop	Operator must suspend injection, reduce pressure and monitor seismicity and ground motion for any further events before potentially resuming

Table 29 - Potential Traffic Light System for the prospect site

- Well integrity: Annulus pressure anomaly, sustained temperature deviation (DTS), or cement integrity concern, should lead to operational suspension, integrity testing and remedial intervention if required.
- Seabed morphology (MBES): Detection of new pockmarks, measurable seabed deformation, or persistent acoustic flares should trigger targeted repeat survey, and cross-validation with subsurface data.
- Seabed geochemistry: Sustained pH decrease, porewater chemistry, DIC increase, or carbonate system deviation beyond baseline confidence interval should lead to intensified sampling and integrated subsurface review.
- Water column carbonate system: Confirmed anomaly beyond seasonal baseline variation should trigger targeted vertical profiling and source attribution assessment.

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Monitoring thresholds (Table 30) and corresponding response actions will be reviewed periodically and adjusted according to project phase and updated risk assessment.

Trigger	Indicative response
Reservoir pressure deviation > +15%	Reduce injection rate, revise pressure-management strategy, update dynamic model and reassess fault stability.
Injectivity decline beyond expected envelope	Perform diagnostic testing and adjust operational parameters.
TLS yellow / red condition	Reduce injection and intensify monitoring, or suspend injection and carry out technical review.
Annulus-pressure or DTS anomaly	Suspend operations, perform integrity testing and, if necessary, remedial intervention.
Seabed or water-column anomaly	Launch targeted MBES / geochemical / vertical-profiling campaigns and integrate results with subsurface MMV data.

Table 30 - Trigger thresholds and responses

6.7.7 MMV Cost framework

The total anticipated costs of the MMV programme, excluding the baseline 3D seismic acquisition conducted as part of site characterisation, are estimated to range between approximately €3.2M and €4.6M, based on the monitoring architecture and survey frequency defined in this section (Table 31), and were included in contingency costs in the economic assessment for the Lusitanian basin in D4.11 (Canteli et al. 2026a). This estimate reflects the implementation of the MMV plan under a risk-based and proportionate monitoring strategy, adapted to the scale and duration of the pilot.

The main CAPEX items are the installation of DAS, downhole pressure / temperature / flowrate and annulus monitoring, *SpotLight-type* subsea nodes, and other permanent or semi-permanent seabed systems. The resulting CAPEX is estimated at €1.4M – €1.9M. This range reflects uncertainty primarily associated with the final specification and procurement of subsea monitoring systems.

OPEX are driven by the number and type of monitoring campaigns. The baseline phase includes one-off acquisition campaigns to establish reference conditions. During injection, monitoring is performed at regular intervals, with annual offshore surveys and seasonal environmental measurements. Post-injection monitoring includes a reduced set of verification campaigns. In addition, continuous monitoring systems incur limited annual operating costs. Based on these frequencies and typical offshore campaign costs, the total operational expenditure is estimated at €1.8M and €2.7M for the full pilot duration. This range reflects baseline acquisition, periodic offshore campaigns during injection, post-injection verification, continuous monitoring operation, and well integrity logging

Time-lapse (4D) seismic acquisition is treated as a decision-gated and contingency measure, rather than a baseline monitoring requirement for the pilot phase and are not included in the cost assessment for the MMV.

The main factors capable of increasing MMV costs are:

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- Meteorology and Weather Standby (WOW): The Atlantic coast off Figueira da Foz is highly exposed to severe winter swells and high wind states. If wave heights exceed safe operational limits (typically 2 to 3 metres for seismic streamers or ROV deployment), the crew must "Wait on Weather" (WOW). During WOW, the project still pays the vessel's daily rate without acquiring any data, which can easily inflate a campaign's budget by 15% to 20%.
- Hydrodynamics and Seabed Mobility: Strong bottom currents in the Lusitanian Basin can narrow the safe operational windows for launching and recovering AUVs and ROVs, extending the total days required at sea. Furthermore, high hydrodynamic energy leads to sediment mobility and scour; this may necessitate heavier, more expensive benthic landers to anchor the SpotLight nodes securely or require costly mid-cycle ROV interventions to unbury sensors covered by shifting sands.
- Offshore Supply Chain Volatility: The day rates for DP2 (Dynamic Positioning) survey vessels fluctuate heavily based on competing demand from the offshore wind and oil & gas sectors. Mobilising a specialised vessel during peak summer months (to avoid the winter weather risks) often carries a significant market premium.

Conversely, the main factors capable of reducing costs are:

- Simultaneous Operations (SIMOPS) and Vessel Sharing: The most effective way to reduce the MMV budget is by running integrated environmental campaigns. By utilising a single multi-purpose vessel to simultaneously conduct Multibeam Echosounder (MBES) mapping, CTD and ADCP profiling, and benthic sediment sampling, the project avoids paying for multiple vessel mobilisations and demobilisations.
- Adaptive Risk-Based Escalation: If continuous well-based monitoring (DAS and downhole pressure/temperature) confirms that the CO_2 plume is behaving exactly as predicted by the reservoir models, the project may successfully petition regulators to reduce the frequency of the highly expensive 4D seismic repeat surveys in the later years of the pilot, saving millions.
- Emerging Autonomous Technologies: The rapid commercialisation of Uncrewed Surface Vessels (USVs) and advanced Autonomous Underwater Vehicles (AUVs) offers a massive cost-saving opportunity. Using a USV piloted from shore to conduct routine MBES or water-column surveys can cost a fraction of the daily rate of a fully crewed, 50-metre offshore survey ship.

The estimated cost is consistent with the scale and objectives of the pilot and with the implementation of a risk-based MMV strategy.

Technology	Unit cost
DAS (distributed acoustic sensing) — injection well	€700,000 CAPEX per injector; €25,000/yr O&M
Downhole P/T/Q + annulus monitoring	€150,000 CAPEX per injector; €10,000/yr O&M
CBL/USIT (well integrity logging)	€200,000 per campaign
Natural seismicity baseline	€150,000+ (network + 1 yr recording)).
CO_2 detectors (wellhead / topside)	€10,000 CAPEX + €1,000/yr O&M
CO_2 stream composition / quality	€5,500 per campaign

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Tracer (contingency)	€120,000 per pulse
MBES bathymetry (baseline or repeat)	~€150,000 - €250,000 per campaign
Seabed sediment & porewater geochemistry	~€50,000 - €80,000 per campaign
Biological surveys (BACI / Beyond-BACI)	~€100,000 - €150,000 per campaign
AUV / ROV targeted investigations	~€30,000 - €50,000 per day
Water column monitoring (CTD + carbonate system)	~€20,000 - €40,000 per campaign (Baseline – Occurrence – Post)
Seafloor fixed sensors (acoustic leak / chemical)	€150,000 - €300,000 CAPEX per lander
SpotLight / MPM multipoint seabed system	~€500,000 - €1,000,000+ CAPEX

Table 31 - Indicative unit costs for main MMV components.

6.7.8 Assumptions and limitations

The MMV plan is developed for a pilot-scale offshore injection of less than 100 kt of CO_2 under the present geological and operational understanding of the Lusitanian Basin site. It assumes that the current structural interpretation, the identified storage-complex geometry, and the results of the WP3 reservoir and geomechanical modelling provide a sufficiently robust basis for monitoring design. It also assumes that a baseline environmental campaign will be completed before injection and that key offshore assets and vessels will be available within acceptable weather windows.

At the same time, the plan is subject to practical limitations and uncertainties linked to Atlantic offshore operations. Severe winter swell and strong winds off Figueira da Foz can impose weather standby and materially affect campaign budgets. Strong bottom currents and seabed mobility may reduce the safe launch and recovery windows for AUVs and ROVs and can also require heavier or more robust subsea installations. Finally, day rates for offshore survey vessels are affected by wider market competition, particularly from offshore wind and oil-and-gas activity. These limitations do not alter the conceptual validity of the MMV plan, but they are relevant to scheduling, procurement strategy and the final cost envelope.

The MMV plan is intended to be updated as new data become available, including baseline results, operational monitoring data and improved modelling outcomes. Such updates will be carried out in accordance with adaptive monitoring principles, ensuring that the monitoring programme remains consistent with evolving site understanding, risk assessment and best available technologies.

7. Upper Silesia (Poland)

The CCS concept in Upper Silesia is not being developed as a fully licensed storage site, but rather as a phased feasibility study, enabling gradual reduction of uncertainty and adaptation to industrial demand.

Work within the PilotSTRATEGY project identified the Jurassic saline aquifer system in the Pągów-Milianów region as a suitable storage structure with an estimated capacity of approximately 30 Mt of CO_2. The reservoir properties, including porosity in the 15–19% range and permeability up to several hundred mD, indicate favourable injection conditions, although uncertainty remains regarding heterogeneity and pressure propagation at larger scales.

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At the same time, the region is characterized by a dense concentration of industrial CO_2 sources within a 30–80 km radius, encompassing the energy, cement, steel, and chemical sectors, creating conditions for the development of a CCS node.

The proposed development is based on a phased approach, which was described in D4.5 (Lachén et al., 2025). The initial pilot phase assumes injection of approximately 30 kt CO_2 per year for three years using a single vertical well and road transport of liquefied CO_2. This configuration is not intended to be commercially viable, but rather to test injection efficiency, pressure response, and monitoring strategies under controlled conditions. The pilot serves as a system validation phase, allowing for adjustments to operational parameters and mitigating key uncertainties. Transition to commercial operation is defined by scaling up to approximately 300 kt CO_2 per year over a 25-year period. At this stage, it is assumed that transport will be transferred from road to pipeline, and the injection system will need to evolve accordingly, potentially including additional wells or modified well geometry. System performance at this stage is highly dependent on maintaining sufficient throughput to avoid infrastructure underutilization, particularly with respect to pipeline capital expenditures and long-term monitoring requirements.

From a reservoir perspective, system performance is determined by pressure management, not solely by volumetric capacity. Although the total storage capacity is sufficient for the proposed injection volumes, the main limitation is the ability to sustain injection without excessive pressure buildup. This means that injection cannot be considered a static design problem, but rather a dynamic process requiring continuous adjustment of injection rate, monitoring intensity, and potential well configuration. The monitoring system relies on a combination of underground and surface techniques, including pressure and temperature measurements, seismic methods such as VSP, and later time-lapse seismic surveys, as well as groundwater, soil gas, and atmospheric monitoring. The monitoring strategy is risk-based and involves incorporating preliminary data during the pilot phase, with the aim of optimizing it during commercial operation as a better understanding of system behaviour develops.

The economic evaluation presented in D4.12 conducted for the project confirmed that the pilot phase is not cost-effective as a stand-alone investment. Its value lies in enabling a commercial phase where economies of scale. Longer lifetime of the project and higher CO_2 throughput can improve financial results. In the scenarios assumed in the economic analysis, the project becomes profitable only with higher CO_2 emission allowance prices, which highlights the strong dependence on the dynamics of the EU ETS. Transport infrastructure and long-term monitoring costs remain key cost factors, along with uncertainty related to permits and scheduling.

From a systems perspective, the Upper Silesian case could represent a potential center for a regional CCS network, but its feasibility depends on geological suitability, infrastructure development, and the ability to address regulatory and social constraints. Transition to commercial use requires confirmation that the reservoir can withstand injection under pressure constraints and that economic conditions remain favourable. In this way, the Upper Silesian case can contribute to regional decarbonization while gradually reducing uncertainty through staged implementation.

8. Macedonian Basin (Greece)

The Macedonia Basin, and more specifically the Mesohellenic Trough, should be approached as a storage system whose behaviour is controlled by the interaction between geological capacity,

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pressure conditions, and the way this capacity can be progressively accessed under realistic operating conditions.

Previous PilotSTRATEGY work has already identified the Pentalofos and Eptachori formations as the principal storage units, with indicative storage capacities of approximately 1.02–1.28 Gt CO_2 and 0.13–0.17 Gt CO_2, respectively, confirming that the basin hosts storage volumes of regional significance (Deliverable 4.3 (Canteli et al., 2025a), Deliverable 4.5 (Lachén et al., 2025)).

At the same time, previous assessments have linked the basin to nearby emission sources in West Macedonia, especially the lignite power plant Ptolemaida V, which under operation could provide several million tonnes of CO_2 per year (Deliverable 4.5). This initially described the system as a conventional capture-transport-storage chain.

According to the results of WP4 deliverables, what becomes more relevant is how this capacity can be deployed over time. The Mesohellenic Trough has already been described through a staged development approach, where initial injection focuses on the most accessible parts of the system, particularly the Pentalofos formations, and expands progressively as infrastructure develops and improves. Additionally, this is reflected in the economic financial evaluation, where the system performance depends on maintaining sufficient CO_2 throughput and avoiding underutilisation of infrastructure (Deliverable 4.3; Koukouzas et al, 2023).

The Mesohellenic Trough behaves as a structurally controlled reservoir where injectivity and pressure evolution define system performance. In practice, this limits the extent to which injection can be concentrated in a small number of wells and requires a more distributed approach, both spatially and across different stratigraphic intervals. This is also outlined in D4.9 (Canteli et al., 2025b), where the Macedonia Basin is assessed as a full-chain scenario including capture, transport and injection, with indicative economics based on short source-to-sink distances, three injection wells, storage-site CAPEX on the order of 301 M€, and a positive NPV under the assumed carbon price scenario (Deliverable 4.9).

In practical terms, this means that commercial deployment must be treated as a progressive activation of multiple stratigraphic and structural compartments, where injection rates, well placement and transport build-out evolve together. The Greek case is better understood as a transnational CCS hub in development rather than as a single storage site. The longer-term scenario allows for broader source integration and even cross-border relevance within Southeastern Europe (Deliverable 4.5).

The available evidence supports the main elements of this transition: the presence of significant storage resources, relatively favourable distances for transport, and an economic framework that becomes viable when the system operates close to its design capacity.

The next step is to demonstrate that the system can sustain injection under pressure constraints and that uncertainties related to reservoir behaviour can be reduced to a level compatible with large-scale deployment.

The basin represents a system that becomes operational through staged development. Its value lies in the combination of geological capacity and the possibility to integrate this capacity within a broader CCS network. The Mesohellenic Trough can function as a large-scale storage component within the Greek CCS landscape, with the potential to support wider regional decarbonisation needs.

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10. Annex 1 – Risk Register for a pilot in Paris Basin

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RISK REGISTER

Paris Basin

Projet Phase: Pilot

Last Update: 14/11/2025

Cod	#	Threat/Opportunity	Cat	Identified By	Risk Identification: Description	Causes		Effects		Factor	Current Assessment: Probability	Impact	Rating	Selected Probability	Selected Impact	Rating	Priority of Response	Response strategy	Threat Responses	Response description	After Response: Probability	Impact	Rating
T1	1	T	T-Technological	WP4	Vertical leakage through caprock (sealing efficiency)	C1	Due to the presence of an undetected high permeability zone	E1	Elevated concentration of CO2 in the atmosphere	Environmental	VL	H	5	VL	VH	7	Low	Accept	R1	subsurface & storage monitoring	VL	H	5
						C2	Discontinuities (fractures, faults) in the caprock	E2	Elevated concentration of CO2 (CH4 and/or H2S) in the groundwater of Albian/Aptian aquifer	Cost (CAPEX / ABEX)	VL	VH	7						R2				
						C3	Geochemical degradation of caprock	E3	Less CO2 stored	Company image	VL	H	5						R3				
						C4	Fracturing of the caprock induced during injection	E4	Less CO2 stored and elevated concentration of CO2 in the overburden	Environmental	VL	VH	7						R4				
						C5		E5											R5				
						C6		E6											R6				
						C7		E7											R7				
						C8		E8											R8				
T2	2	T	T-Technological	WP5	Vertical leakage along fractures	C1	Fracturing of the caprock induced by injection, over-pressurisation around well	E1	Elevated concentration of CO2 in the atmosphere	Environmental	VL	VH	7	L	H	6.5	Medium	Mitigate	R1	subsurface & storage monitoring	VL	H	5
						C2	Fracturing of the caprock induced by injection, Reservoir over-pressurisation	E2	Elevated concentration of CO2 (and 222Rn, CH4 and/or H2S) in the groundwater or atmosphere	Cost (CAPEX / ABEX)	L	H	6.5						R2				
						C3	Via fractures in caprock	E3	CO2 accumulation in a secondary reservoir	Cost (CAPEX / ABEX)	VL	H	5						R3				
						C4	No observed/interpreted faults from seismic data	E4		Company image									R4				
						C5	Heterogeneities can result in directional variations in permeability (fluids mobility)	E5	Fluid migration	Company image									R1				
						C6		E6											R2				
						C7		E7											R3				
						C8		E8											R4				
T3	3	T	T-Technological	WP4	Lateral leakage	C1	Movement of CO2 outside the lateral boundary	E1	Elevated concentration of CO2 in the atmosphere	Environmental	VL	VH	7	VL	VH	7	Medium	Mitigate	R1	subsurface & storage monitoring	VL	H	5
						C2	Interaction with other resources	E2	Elevated concentration of CO2 (and 222Rn, CH4 and/or H2S) in the groundwater	Cost (CAPEX / ABEX)	VL	H	5						R2				
						C3	High CO2 injection rates	E3	Less CO2 Stored	Cost (CAPEX / ABEX)	VL	H	5						R3				
						C4	Non-expected leakage paths associated with uncertainties in the geological/reservoir model	E4	Contaminate near-surface aquifers, contamination of potable water supplies	Environmental	VL	VH	7						R4				
						C5	Displacement of saline formation fluids	E5	Storage redimensioning	Company image	L	M	6.5						R5				
						C6		E6											R6				
						C7		E7											R7				
						C8		E8											R8				
T4	4	T	T-Technological	WP4	Lateral leakage	C1	Movement of CO2 outside the lateral boundary	E1	Elevated concentration of CO2 in the atmosphere	Environmental							Medium	Mitigate	R1				
						C2	Interaction with other resources	E2	Elevated concentration of CO2 (and 222Rn, CH4 and/or H2S) in the groundwater	Cost (CAPEX / ABEX)									R2				
						C3	CO2 plume has reached the existing faults of the storage complex due to the processes related to the transport of CO2 in formation water	E3	Less CO2 Stored	Company image									R3				
						C4	High CO2 injection rates	E4	Faults reactivation or lateral leakage										R4				
						C5	Non-expected leakage paths associated with uncertainties in the geological/reservoir model	E5	Contaminate near-surface aquifers, contamination of potable water supplies										R1				
						C6	Displacement of saline formation fluids	E6	Storage redimensioning										R2				
						C7		E7											R3				
						C8		E8											R4				
T5	5	T	T-Technological	WP4	Leakage from operating well	C1	Well blow-outs during drilling	E1	Elevated concentration of CO2 in the atmosphere	Environmental	L	M	6.5	L	H	6.5	Medium	Mitigate	R1	well monitoring (wellhead & inwell)	VL	H	5
						C2	Leakage through well loss of integrity	E2	Elevated concentration of CO2 (and 222Rn, CH4 and/or H2S) in the groundwater	Company image	L	H	6.5						R2				
						C3	Inadequate wellbore construction, comprising the design, lining, drilling and/or completion of the well	E3	Less CO2 stored / lower injection rate	Cost (CAPEX / ABEX)	L	M	6.5						R3				

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ID	No.	Type	Category	WP	Risk	C	Cause	E	Effect	Impact	P	S	Score	P	S	Risk	Level	Response	R	Mitigation	P	S	Residual
						C4	Failure of one or more well barrier elements	E4	Major maintenance works on the well or plugging the well		VL	H	5						R4				
						C5	Overpressure near wellbore	E5											R1				
						C6		E6											R2				
						C7		E7											R3				
						C8		E8											R4				
T6	6	T	T-Technological	WP4	Leakage from legacy abandoned well	C1	No barrier installed over the storage zone to be pressurized (well remediation)	E1	Elevated concentration of CO2 in the atmosphere	Environmental	VL	M	3.5	VL	VH	7	Low	Accept	R1	storage monitoring	VL	H	5
						C2	Inadequate wellbore construction, comprising the design, lining, drilling and/or completion of the well	E2	Less CO2 stored / lower injection rate	Company image	VL	VH	7						R2				
						C3	Failure of one or more well barrier elements	E3	Major maintenance works on the well or plugging the well	Cost (CAPEX / ABEX)	VL	H	5						R3				
						C4		E4											R4				
						C5		E5											R1				
						C6		E6											R2				
						C7		E7											R3				
						C8		E8											R4				
T7	7	T	T-Technological	WP4	Migration of formation brine outside expected boundaries	C1	Increased displacement of high salinity formation	E1	Interaction with other resources	Environmental	H	VL	4	H	VL	4	Low	Accept	R1	subsurface & storage monitoring	H	VL	4
						C2	Pressure wave created by CO2 injection travels much further than the physical CO_2 front, therefore causing the displacement of saline formation fluids	E2	Migration to shallow aquifers, causing the possible salinization of freshwater resources	Company image	VL	VL	1						R2				
						C3	Existence of high-conductivity pathways	E3		Cost (CAPEX / ABEX)	VL	VL	1						R3				
						C4		E4											R4				
						C5		E5											R1				
						C6		E6											R2				
						C7		E7											R3				
						C8		E8											R4				
T8	8	T	T-Technological	WP4	Induced seismicity	C1	Abnormal increasing of seismic events occurrence in a given area than those retrieved from the historical seismicity chart	E1	Perceptible earthquakes	Environmental	VL	VH	7	VL	VH	7	High	Mitigate	R1	subsurface & surface monitoring	L	VL	2
						C2	Loss of mechanical integrity in the reservoir, leading induced seismicity on other subsurface structures	E2	Elevated concentration of CO2 (and 222Rn, CH4 and/or H2S) in the groundwater or surface	Company image	VL	VH	7						R3				
						C3		E3	Loss of containment of a well	Cost (CAPEX / ABEX)	VL	VH	7						R3				
						C4		E4	Mechanical changes of the reservoir/caprock	People	VL	VH	7						R4				
						C5		E5	Damage to third parties infrastructures	Cost (CAPEX / ABEX)	VL	M	3.5						R1				
						C6		E6											R2				
						C7		E7											R3				
						C8		E8											R4				
T9	9	T	T-Technological	WP4	Disruption by another activity	C1	Different administrative control of CO2 storage after closure of project	E1	Elevated concentration of CO2 in the atmosphere	Environmental	VL	H	5	VL	H	5	Low	Accept	R1	Subsurface, storage & surface monitoring	VL	H	5
						C2	Deliberate human actions	E2	Elevated concentration of CO2 (and 222Rn, CH4 and/or H2S) in the groundwater	People	VL	H	5						R2				
						C3	Development of new infrastructure close to the storage complex	E3	Loss of containment of the CO2	Environmental	VL	H	5						R3				
						C4	Drilling new wells	E4	Loss of containment of the CO2	Cost (CAPEX / ABEX)	VL	H	5						R4				
						C5		E5											R1				
						C6		E6											R2				
						C7		E7											R3				
						C8		E8											R4				
T10	10	T	T-Technological	WP4	Changes in groundwater flow, within the reservoir or in other layers of the storage complex	C1	High CO2 injection rates	E1	Modified hydrology and hydrogeology	Environmental	H	VL	4	H	VL	4	Low	Accept	R1	Subsurface monitoring	H	VL	4
						C2	Dissolution and/or precipitation of minerals due to the injection of CO2, since the CO_2 reaction with the host rock	E2	elevated concentration of CO2 (and 222Rn, CH4 and/or H2S) in the groundwater	People	H	VL	4						R2				
						C3	Existence of high conductivity pathways	E3	storage redimensioning	Company image	H	VL	4						R3				
						C4	Mechanical changes of the reservoir/caprock	E4											R4				
						C5		E5											R1				
						C6		E6											R2				
						C7		E7											R3				
						C8		E8											R4				
T11	11	T	T-Technological	WP4	Loss of Injectivity	C1	Reduced porosity due to chemical precipitation	E1	Less CO2 stored, lower injection rates, insufficient for project objectives	Profitability (Production)	VL	M	3.5	VL	H	5	High	Mitigate	R1	well monitoring (wellhead & inwell)	L	L	4.5
						C2	Physical pore obstructions	E2	Wells will require more frequent intervention	Cost (CAPEX / ABEX)	VL	H	5						R2				
						C3	Clay swelling	E3	Additional wells required	Cost (CAPEX / ABEX)	VL	H	5						R3				
						C4	Borehole deformation	E4											R4				
						C5	Geological heterogeneities	E5											R1				
						C6		E6											R2				
						C7		E7											R3				
						C8		E8											R4				
T12	12	T	T-Technological	WP4	Lower than expected capacity	C1	Porosity/permeability reduction due to chemical precipitation	E1	Less CO2 stored	Profitability (Production)	VL	L	2.5	VL	L	2.5	High	Mitigate	R1	storage monitoring	VL	L	2.5
						C2	Clay swelling	E2											R2				
						C3	Geological heterogeneities	E3											R3				
						C4	Undetected local permeability heterogeneities	E4											R4				
						C5		E5											R1				
						C6		E6											R2				
						C7		E7											R3				

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						C8	E8										R4				
T13	13	T	T-Technological	WP4	Reservoir pressurization due to unexpected compartmentalisation	C1 Existence or non-detected geological heterogeneities C2 C3 C4 C5 C6 C7 C8	E1 Less CO2 stored E2 Reduction of estimated capacity E3 Different injection strategy E4 Storage redimensioning E5 Early abandonment E6 E7 E8	Profitability (Production)	VL	L	2.5	VL	L	2.5	Medium	Mitigate	R1 storage monitoring R2 R3 R4 R1 R2 R3 R4	VL	L	2.5
T14	14	T	T-Technological	WP4	Accidental Over-fill	C1 More CO2 injected than planned C2 Reservoir storage capacity is smaller than calculated C3 Existence of more highly permeable conduits than initially recognized C4 C5 C6 C7 C8	E1 Elevated concentration of CO2 in the atmosphere E2 Elevated concentration of CO2 (and 222Rn, CH4 and/or H2S) in the groundwater E3 Increased pressure of the reservoiraffecting the caprock and inducing seismicity E4 E5 E6 E7 E8	Environmental Company image	VL VL	M M	3.5 3.5	VL	M	3.5	Low	Accept	R1 None R2 R3 R4 R1 R2 R3 R4	VL	H	5
T15	15	T	T-Technological	WP4	Uplift or subsidence of ground	C1 Mass injected and pressure increment progressively change ground level C2 C3 C4 C5 C6 C7 C8	E1 damage to third parties installations E2 E3 E4 E5 E6 E7 E8	People Environmental Company image	VL VL VL	L L H	2.5 2.5 5	VL	H	5	Low	Accept	R1 surface monitoring R2 R3 R4 R1 R2 R3 R4	VL	L	2.5
T16	16	T	P-Political	ISO27918	Uncertainty in CCS policy support or unexpected regulatory changes	C1 Shifts in national or EU climate policy, political turnover, or lack of long-term regulatory clarity. C2 C3 C4 C5 C6 C7 C8	E1 Project delays E2 Project redesigns, due to non-compliance or loss of eligibility for incentives. E3 Project cancelations due to non-compliance or loss of eligibility for incentives. E4 E5 E6 E7 E8	Schedule Cost (CAPEX / ABEX) Profitability (Production)	L L L	H H VH	8.5 8.5 13	L	VH	13	High	Mitigate	R1 R2 R3 R4 R1 R2 R3 R4	L	VH	13
T17	17	T	R-Regulatory & Permitting	ISO27918	Delays or inability to obtain key permits	C1 Bureaucratic inefficiencies, unclear permitting pathways, or conflicting jurisdictional requirements. C2 C3 C4 C5 C6 C7 C8	E1 Missed project milestones, increased costs, or inability to proceed to execution phase. E2 E3 E4 E5 E6 E7 E8	Schedule	M	H	14	M	H	14	High	Mitigate	R1 R2 R3 R4 R1 R2 R3 R4	M	H	14
T18	18	T	E-Economical	ISO27918	Lack of financial incentives or changes in CO_2 pricing	C1 Market-based mechanisms (e.g., ETS) underperforming or being restructured. C2 C3 C4 C5 C6 C7 C8	E1 Not relevant for pilot E2 E3 E4 E5 E6 E7 E8	Profitability (Production)									R1 R2 R3 R4 R1 R2 R3 R4			
T19	19	T	E-Economical	ISO27918	Unexpected construction or operational cost changes	C1 Immature supply chains, inflation, or underestimated technical complexity. C2 C3 C4 C5 C6 C7 C8	E1 Budget overruns, need for re-scoping, or reduced return on investment. E2 E3 E4 E5 E6 E7 E8	Cost (CAPEX / ABEX)	L	H	8.5	L	H	8.5	Medium	Mitigate	R1 R2 R3 R4 R5 R6 R7 R8	L	M	6.5
T20	20	T	E-Economical	ISO27918	Uncertainty in CO_2 supply	C1 Emitters not committing to long-term contracts or underperforming capture facilities. C2 C3 C4 C5 C6 C7 C8	E1 Underutilized storage infrastructure, reduced economies of scale, or stranded assets. E2 E3 E4 E5 E6 E7 E8	Profitability (Production)	VH	H	30	VH	H	30	High	Transfer	R1 specification of the CO2 (external) while local CO2 is pure (H2 base) R2 R3 R4 R1 R2 R3 R4	VL	L	2.5

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T21	21	T	S-Social	ISO27918	Public opposition or lack of social acceptance	C1	Lack of early engagement with local communities, misinformation about CCS safety or environmental impact, or historical distrust in industrial projects.	E1	Delays in permitting, legal challenges, reputational damage, or even project cancellation due to public pressure.	Schedule	M	H	14	M	H	14	Medium	Mitigate	R1	implement local engagement	M	H	14
						C2		E2											R2				
						C3		E3											R3				
						C4		E4											R4				
						C5		E5											R1				
						C6		E6											R2				
						C7		E7											R3				
						C8		E8											R4				
T22	22	T	S-Social	ISO27918	Ineffective risk communication with stakeholders	C1	Use of overly technical language, absence of transparent communication plans, or failure to address stakeholder concerns.	E1	Misunderstandings, erosion of trust, increased resistance from stakeholders, and reduced likelihood of public or political support.	Schedule	M	H	14	M	H	14	Medium	Mitigate	R1	implement QHSE policy	L	M	6.5
						C2		E2											R2				
						C3		E3											R3				
						C4		E4											R4				
						C5		E5											R1				
						C6		E6											R2				
						C7		E7											R3				
						C8		E8											R4				
T23	23	T	EN-Environmental & Safety	ISO27918	Lack of maintenance or emergency procedures	C1	Inadequate operational planning, underfunding of O&M activities, or absence of trained personnel and response protocols.	E1	Increased likelihood of equipment failure, environmental incidents, regulatory non-compliance, or safety hazards for personnel and the public.	People	L	H	6.5	L	H	6.5	Medium	Mitigate	R1	implement QHSE policy	L	L	4.5
						C2		E2		Company image	L	H	6.5						R2				
						C3		E3											R3				
						C4		E4											R4				
						C5		E5											R5				
						C6		E6											R2				
						C7		E7											R3				
						C8		E8											R4				
T24	24	T	EN-Environmental & Safety	ISO27918	Corrosion or material issues in pipelines or wells	C1	Presence of impurities in the CO_2 stream (e.g., water, H_2S, SO_X), poor material selection, or insufficient monitoring and inspection.	E1	Structural degradation, leaks, unplanned shutdowns, environmental contamination, and high repair or replacement costs.	Cost (CAPEX / ABEX)	VL	H	5	VL	H	5	High	Mitigate	R1	well monitoring (inwell)	VL	VL	1
						C2		E2		People	VL	H	5						R2				
						C3		E3											R3				
						C4		E4											R4				
						C5		E5											R1				
						C6		E6											R2				
						C7		E7											R3				
						C8		E8											R4				
T25	25	T	EN-Environmental & Safety	ISO27918	Unforeseen environmental impacts	C1	Incomplete baseline environmental studies, unexpected interactions between injected CO_2 and subsurface ecosystems, or cumulative impacts with other projects.	E1	Regulatory intervention, need for additional mitigation measures, reputational harm, or project suspension.	Company image	L	M	6.5	L	M	6.5	Medium	Mitigate	R1	implement QHSE process&response	L	M	6.5
						C2		E2		Environmental	VL	M	3.5						R2				
						C3		E3		Cost (CAPEX / ABEX)	L	M	6.5						R3				
						C4		E4											R4				
						C5		E5											R1				
						C6		E6											R2				
						C7		E7											R3				
						C8		E8											R4				
T26	26	T	EN-Environmental & Safety	ISO27918	Conflicts with other subsurface or surface land uses	C1	Overlapping rights or activities such as agriculture, water extraction, geothermal energy, or protected natural areas.	E1	Legal disputes, restricted access to project areas, increased permitting complexity, or forced redesign of infrastructure layout.	Cost (CAPEX / ABEX)	L	M	6.5	L	M	6.5	Medium	Mitigate	R1	storage monitoring	L	L	4.5
						C2		E2											R2				
						C3		E3											R3				
						C4		E4											R4				
						C5		E5											R5				
						C6		E6											R2				
						C7		E7											R3				
						C8		E8											R4				
T27	27	T	T-Technological	ISO27918	Unexpected variations in CO_2 composition	C1	Differences in capture technologies or industrial sources.	E1	Corrosion, reduced injectivity, or need for additional treatment or monitoring.	OPEX	VL	L	2.5	VL	L	2.5	Medium	Mitigate	R1	none	VL	L	2.5
						C2		E2		Profitability (Production)	VL	L	2.5						R2				
						C3		E3											R3				
						C4		E4											R4				
						C5		E5											R1				
						C6		E6											R2				
						C7		E7											R3				
						C8		E8											R4				
T28	28	T	T-Technological	ISO27918	Mismatched performance between system components (capture, transport, storage)	C1	Asynchronous development timelines, differing technical standards, or lack of coordination between project partners.	E1	Bottlenecks, underutilization of infrastructure, or failure to meet injection/storage targets.	Profitability (Production)	L	M	6.5	L	M	6.5	Medium	Mitigate	R1	management of development plan and Long-lead item planning	M	L	5
						C2		E2											R2				
						C3		E3											R3				
						C4		E4											R4				
						C5		E5											R1				
						C6		E6											R2				
						C7		E7											R3				
						C8		E8											R4				

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T29	29	T	P-Political		Lack of internal support within the company due to CCS competing with other business lines	C1	CCS competes with other business within promoting company	E1	Delay	Schedule										R1				
						C2		E2	Cancel	Cost (CAPEX / ABEX)										R2				
						C3		E3												R3				
						C4		E4	Not relevant for pilot											R4				
						C5		E5												R1				
						C6		E6												R2				
						C7		E7												R3				
						C8		E8												R4				
T30	30	T	P-Political	WP4	Local authority opposition despite national-level support	C1	Opposition from local authorities	E1	Delayed approval	Schedule	L	M	6.5	L	H	6.5		Low	Accept	R1	implement local community engagment & exchange (WP6)	L	M	6.5
						C2		E2		Cost (CAPEX / ABEX)	L	H	6.5							R2				
						C3		E3												R3				
						C4		E4												R4				
						C5		E5												R1				
						C6		E6												R2				
						C7		E7												R3				
						C8		E8												R4				
T31	31	T	L-Legal	WP4	Competitor securing acreage before Pilot (first-mover disadvantage)	C1	A competitor may request the permit in the same or nearby location before Pilot Strategy	E1	Higher cost of farm-in into competitors acreage	Cost (CAPEX / ABEX)	VH	H	20	VH	H	20		High	Mitigate	R1	negociate a business agreement to implement pilot together	H	M	12
						C2		E2		Company image										R2				
						C3		E3												R3				
						C4		E4												R4				
						C5		E5												R1				
						C6		E6												R2				
						C7		E7												R3				
						C8		E8												R4				
T32	32	T	L-Legal	WP4	Uncertainty in commercial contracts affecting design and schedule	C1	Actual contracts specs different from assumed	E1	Schedule Delays	Schedule										R1				
						C2		E2	Not relevant for pilot	Cost (CAPEX / ABEX)										R2				
						C3		E3												R3				
						C4		E4												R4				
						C5		E5												R1				
						C6		E6												R2				
						C7		E7												R3				
						C8		E8												R4				
T33	33	T	T-Technological	WP4	Lack of sufficient power distribution infrastructure for hub operations	C1	Lack of sufficient power distribution infrastructure in the area	E1	Need to upgrade power distribution network	Cost (CAPEX / ABEX)	VL	L	2.5	VL	L	2.5		Low	Accept	R1	dialoge with the plant to acces utilities	VL	L	2.5
						C2		E2		Schedule	VL	L	2.5							R2				
						C3		E3												R3				
						C4		E4												R4				
						C5		E5												R1				
						C6		E6												R2				
						C7		E7												R3				
						C8		E8												R4				
T34	34	T	T-Technological	WP4	Dense-phase CO_2 pipeline rupture near populated areas (safety and design implications)	C1	Unintended external damage (e.g., during works in the pipeline area)	E1	Significant release of high-pressure CO2, leading to dry ice formation in the area	People	L	M	6.5	L	M	6.5		Medium	Mitigate	R1	active/passive security during operation	L	L	4.5
						C2	Terrorist attack	E2	Potential for a running ductile fracture event in the pipeline, if not properly designed	Company image	VL	H	5							R2				
						C3		E3												R3				
						C4		E4												R4				
						C5		E5												R1				
						C6		E6												R2				
						C7		E7												R3				
						C8		E8												R4				
T35	35	T	R-Regulatory & Permitting	WP4	NZIA adopted by French authorities	C1	Pressure by EC on implementation	E1	Reduced time for permits	Schedule	L	M	6.5	L	M	6.5		Medium	Accept	R1	none	L	M	6.5
						C2		E2												R2				
						C3		E3												R3				
						C4		E4												R4				
						C5		E5												R1				
						C6		E6												R2				
						C7		E7												R3				
						C8		E8												R4				
T36	36	T	E-Economical	WP4	Access to EU/national funds	C1	Obtain funds granted by EC as incentive for descarbonization	E1	lack of such funding at EU level	Profitability (Production)	VH	H	20	VH	H	20		Medium	Accept	R1		VH	H	20
						C2		E2												R2				
						C3		E3												R3				
						C4		E4												R4				
						C5		E5												R1				
						C6		E6												R2				
						C7		E7												R3				
						C8		E8												R4				

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11. Annex 2 – Thermodynamic analysis of the conditioning process for Lusitanian basin

11.1.1 Analysis

11.1.1.1 Preliminary analysis

The following analysis evaluates the thermodynamic and operational performance of the carbon dioxide conditioning system, structured into three critical blocks that define the viability of the process.

11.1.1.1.1 Conditioning at the capture plant

The temperature-entropy (T-s) and temperature-density (T-ρ) diagrams in Figure 3-20 illustrate the evolution of CO_2 from its post-capture gaseous state to its stabilisation as a subcooled liquid.

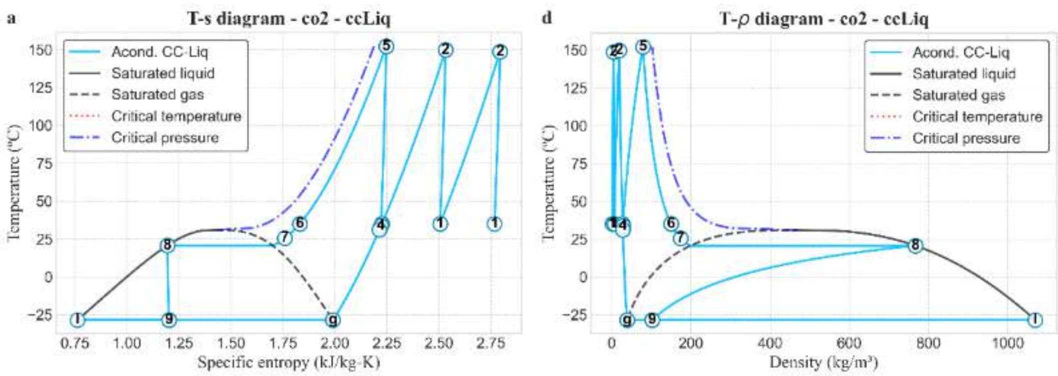

Figure 46 - Diagrams: a) temperature-entropy (T-s), and b) temperature-density (T-ρ).

- **(1-6)** The sequence demonstrates a **fractional compression strategy** (Multi-stage Compression with Intercooling) designed to minimise the total compression work and control the discharge temperature.
- **(6-8) Condensation and Phase Change:** This is the most critical area for the external refrigeration system. The horizontal segment between points 7 and 8 represents the phase change at approximately 20 °C (in the preliminary design). This is where latent heat is extracted by the auxiliary refrigeration cycle.
- **(8-9 and L) Final Cooling and Storage:** Following expansion and separation, the end point (L) represents the conditioned CO_2 as a subcooled liquid.

Table 32 details the evolution of CO_2 through the compression, cooling, and phase separation stages.

Reference	Pressure (bar)	Temp. (ºC)	x	Enthalpy (kJ/kg)	Entropy (kJ/kgK)	Density (kg/m3)
01 Inlet	1	35	-1	514.40	2.76	1.72
02 Compressor A (01)	3.87	148.6	-1	616.60	2.79	4.88

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01 Cooler A (01)	3.87	35	-1	511.89	2.50	6.77
02 Compressor A (02)	15	149.7	-1	612.68	2.53	19.19
03 Cooler A (02)	15	35	-1	501.59	2.22	27.70
04 Mix	15	33.6	-1	500.21	2.22	27.86
05 Compressor B	58.1	152.0	-1	594.94	2.24	78.80
06 Cooler B	58.1	35	-1	445.72	1.83	149.99
07 Recuperator-hot	58.1	25.5	-1	423.94	1.75	174.18
08 Refrigeration	58.1	20.6	0	257.91	1.19	766.92
09 Main expander	15	-28.5	0.36	244.03	1.20	102.23
09 Liquid - Storage	15	-28.5	0	136.41	0.76	1069.45
09 Gas - Recirculation	15	-28.5	1	436.92	1.99	39.00
10 Secondary expander	15	-28.5	1	436.92	1.99	39.00
11 Recuperator-cold	15	31	-1	497.74	2.21	28.16

Table 32 - Thermodynamic Properties – CO2 Conditioning at capture plant

Density Increase: The desired increase in fluid density is observed, rising from 1.73 kg/m³ at the inlet to 1069.45 kg/m³ at the liquid transport state (15 bar, -28.5 ºC).

Compression Strategy: The system employs three compression stages (Compressors A1, A2, B), where discharge temperatures are maintained under control near 150 °C. Each cooling stage (Cooler A1, A2, B) prepares the gas for more efficient subsequent compression by reducing its specific volume.

Design Mass Flow: The design mass flow is the same as in the reconditioning process (27.78 kg/s of CO_2). This implies a filling time per container of 16.80 min, completing the filling process for 28 containers in 6.58 hours of continuous operation. Changes to the design mass flow have a direct impact on the sizing of the process equipment.

Liquefaction and Separation: At point 08 (Refrigeration), the fluid is already a saturated liquid (x=0) at 58.09 bar. Upon expansion to point 09 (Storage) at 15 bar, the temperature drops to -28.52 °C. At this stage, phase separation occurs, and the recirculation gas is returned to the process (point 11) to recover thermal energy in the recuperator. It is noted that the recirculated mass flow (x=0.36) reaches a high value; this could be minimised by reducing the condensation pressure (and temperature).

Table 33 summarises the mechanical power requirements (work) and thermal demand (heat) for each unit of the CO_2 conditioning process.

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Equipment	Flow rate (kg/s)	ΔEnthalpy (kJ/kg)	Power (kW)	Heat (kWth)	Units	Inlet	Outlet
Compressor A (01)	27.78	-102.19	-2838.78	0	P(bar)	1	3.87
Cooler A (01)	27.78	-104.71	0	-2908.56	T(C)	148.6	35
Compressor A (02)	27.78	-100.78	-2799.58	0	P(bar)	3.87	15
Cooler A (02)	27.78	-111.08	0	-3085.71	T(C)	149.7	35
Compressor B	43.27	-94.728	-4099.42	0	P(bar)	15	58.1
Cooler B	43.27	-149.22	0	-6457.78	T(C)	152.0	35
Recuperator hot	43.27	-21.78	0	-942.509	T(C)	35	25.5
Recuperator cold	15.49	60.82	0	942.5095	T(C)	-28.5	31
Refrigeration	43.27	-166.03	0	-7184.89	T(C)	25.5	20.6
Main expander	43.27	13.88	600.78	0	P(bar)	58.09	15
Secondary expander	15.49	0	0	0	P(bar)	15	15

Table 33 - Energy Balance

System Demand: The system exhibits a significant total compression load, with Compressor B showing the highest consumption (-4099.42 kW). This is due to it handling a higher mass flow (43.27 kg/s) compared to the initial stages, resulting from the integration of recirculation streams. Negative values denote energy consumed by the system.

The Refrigeration unit requires the extraction of 7184.89 kWth to complete the CO_2 phase change at pressures near the critical point. In this region, the latent heat of vaporisation necessitates a high-capacity external refrigeration system using ammonia (NH_3).

The refrigeration system operates under a simple heat pump compression cycle, designed to provide the required cooling capacity at the CO_2 liquefaction node (Point 08 of the previous process). The cycle operates between pressures of 7.4 bar and 13.5 bar. Other configurations are valid, provided they can extract the required thermal power at the necessary temperature.

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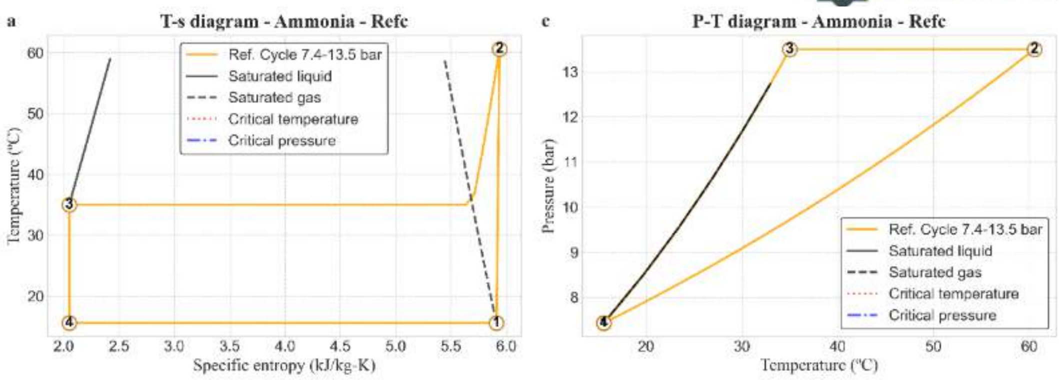

Figure 47 - Diagrams of the compression refrigeration cycle considered in the design: a) temperature-entropy (T-s), and b) temperature-density (T-ρ)

The refrigerant path is defined by the following four fundamental states:

- Compression (1 - 2): Ammonia vapour enters the compressor as saturated vapour at a low temperature (approx. 16 °C). It is compressed to 13.5 bar, raising its temperature to 60 °C. This thermal increase allows the heat to be subsequently rejected into the environment (air or cooling water).
- Condensation (2 - 3): The superheated vapour is cooled and condensed at a constant pressure. The horizontal segment at 35 °C indicates the phase change where the ammonia releases heat to the external sink. At point 3, the refrigerant is a saturated liquid.
- Expansion (3 - 4): The liquid ammonia passes through an expansion valve. The temperature drops sharply from 35 °C to 16 °C. At this point, the refrigerant enters the mixture zone (wet vapour), ready to absorb heat.
- Evaporation / Heat Absorption (4 - 1): This is the coupling point with the CO_2 process. The ammonia absorbs sensible and latent heat from the carbon dioxide, evaporating completely until it returns to the saturated vapour state (Point 1).

Table 34 for the refrigeration cycle reflects an optimised design operating within a thermal range of 15.6 °C to 60.5 °C, enabling heat transfer from the CO_2 conditioning process.

Reference	Pressure (bar)	Temp. (ºC)	x	Enthalpy (kJ/kg)	Entropy (kJ/kgK)	Density (kg/m3)
Refc 01 Compressor in	7.42	15.6	1	1622.22	5.90	5.83
Refc 02 Compressor out	13.45	60.5	-1	1712.49	5.93	9.18
Refc 03 Expander in	13.45	35	0	511.55	2.04	587.58
Refc 04 Expander out	7.42	15.6	0.074	507.96	2.05	70.18

Table 34 - Refrigeration Cycle Properties (NH3)

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The evaporation temperature of NH_3 (16 °C) is lower than the liquefaction temperature of CO_2 (20.59 °C), thereby ensuring the thermal gradient required for heat transfer.

Equipment	Flow rate (kg/s)	ΔEnthalpy (kJ/kg)	Power (kW)	Heat (kWth)	Units	Inlet	Outlet
Refc Compressor	6.45	-90.26	-582.04	0	P(bar)	7.43	13.5
Refc Expander	6.45	3.59	23.14	0	P(bar)	13.45	7.43
Refc Condenser	6.45	-1200.94	0	-7743.79	T(C)	60.5	35
Refc Evaporator	6.45	1114.26	0	7184.89	T(C)	15.6	15.6

Table 35 - Energy Balance of the External Refrigeration Cycle (NH3)

The Evaporator serves as the junction point (heat exchanger) with the CO_2 process. It is observed to absorb **7184.89 kWth**, which matches the thermal load required for carbon dioxide liquefaction identified in the previous analysis. The constant temperature (15.6 °C) indicates that the ammonia is utilising its latent heat of vaporisation to absorb energy efficiently. The Condenser must evacuate **7743.79 kWth** into the environment.

The refrigeration **Coefficient of Performance (COP)** is approximately **12.3**. This value is remarkably high due to the low pressure differential managed (7.4 to 13.5 bar).

$$COP = {}^{Thermal\ power}/_{Compression\ power} = {}^{7184.89\ kW}/_{582.04\ kW}$$

11.1.1.1.2 Onboard Reconditioning

This final stage describes the preparation process of liquid CO_2, transported at low temperature (15 bar, -28.5 ºC), for its final disposal (51 bar, 14 ºC).

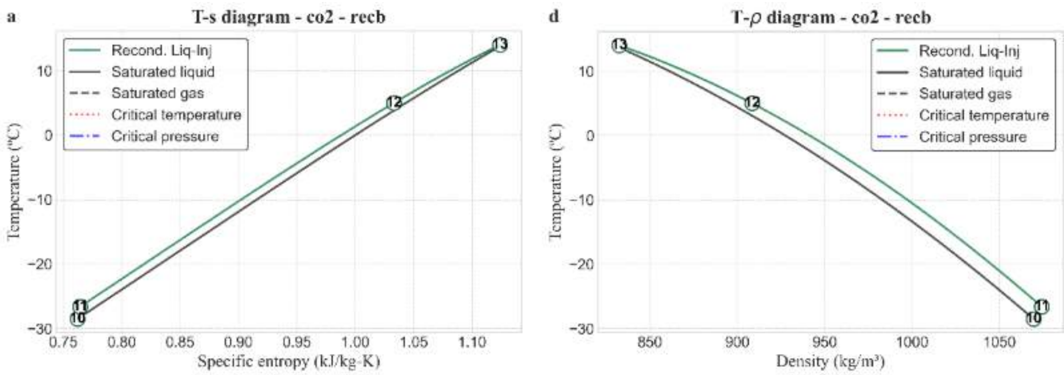

Figure 48 - Reconditioning process diagrams: a) temperature-entropy (T-s), and b) temperature-density (T-ρ)

The process is divided into two main mechanical and thermal manoeuvres:

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- **High-Pressure Pumping (10-11):** As the fluid is an almost incompressible liquid, the temperature increase due to mechanical work is minimal, maintaining the fluid in a high-density state.
- **Conditioning Heating (11-12-13):** This occurs in two stages: i) first, through heat exchange with seawater (15 ºC), which is insufficient to reach the target temperature under these conditions, reaching 10 ºC; and ii) a second heat exchange in an electric heater to reach the target temperature (14 ºC).

By maintaining the fluid in a subcooled state throughout the entire path (Points 10 to 13), it is guaranteed that the boiling point is not reached despite increases in ambient temperature or friction. This design assumes that no pressure losses occur during heat exchange. Should this occur, the pump must pre-emptively compensate for subsequent pressure losses to reach the target pressure and ensure the liquid state of the CO_2 throughout the process.

Reference	Pressure (bar)	Temp. (ºC)	x	Enthalpy (kJ/kg)	Entropy (kJ/kgK)	Density (kg/m3)
Inlet	15	-28.5	0	136.41	0.76	1069.45
Pumping out	51	-26.6	-1	140.31	0.76	1074.21
Seawater heating	51	10	-1	224.43	1.08	870.05
Heater Outlet	51	14	-1	236.59	1.12	832.46

Table 36 - Evolution of Thermodynamic Properties

The results demonstrate an efficient transition while maintaining the fluid in a dense liquid phase. The proposed design takes advantage of the high liquid density to reduce mechanical consumption and uses seawater as the primary heat source for reconditioning.

Equipment	Flow rate (kg/s)	Ah (kJ/kg)	Power (kW)	Heat (kWth)	Unit	Inlet	Outlet
Pump	27.78	-3.9	-108.43	0	P(bar)	15	51
Seawater hx	27.78	84.1	0	2336.5	T(C)	-26.6	10
Electrical heater	27.78	12.2	0	337.93	T(C)	10	14

Table 37 - Equipment and Energy Balance

The power required for pumping is low compared to gaseous compression. The seawater heat exchanger provides the majority of the thermal energy to raise the temperature from cryogenic levels. The electrical heater acts solely as a fine-control step to ensure the fluid reaches the 14 ºC required by the injection protocol. When sizing the heat exchangers, extreme cases must be considered:

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- Excess mass flow in the seawater heat exchanger.
- Lower water temperatures (winter) that may occur during injection periods.

11.1.2 Reduction of condensation pressure in the capture plant

The following section evaluates the system's response to the optimisation of pressure in the liquefaction process, comparing the base case with controlled reductions (0-45%) in the mixing pressure (outlet of compression train A) and in condensation pressure (outlet of compression train B). This sensitivity analysis is fundamental for identifying the optimal balance between the energy consumed by the external refrigeration cycle (which increases) and that of the main process line (which decreases).

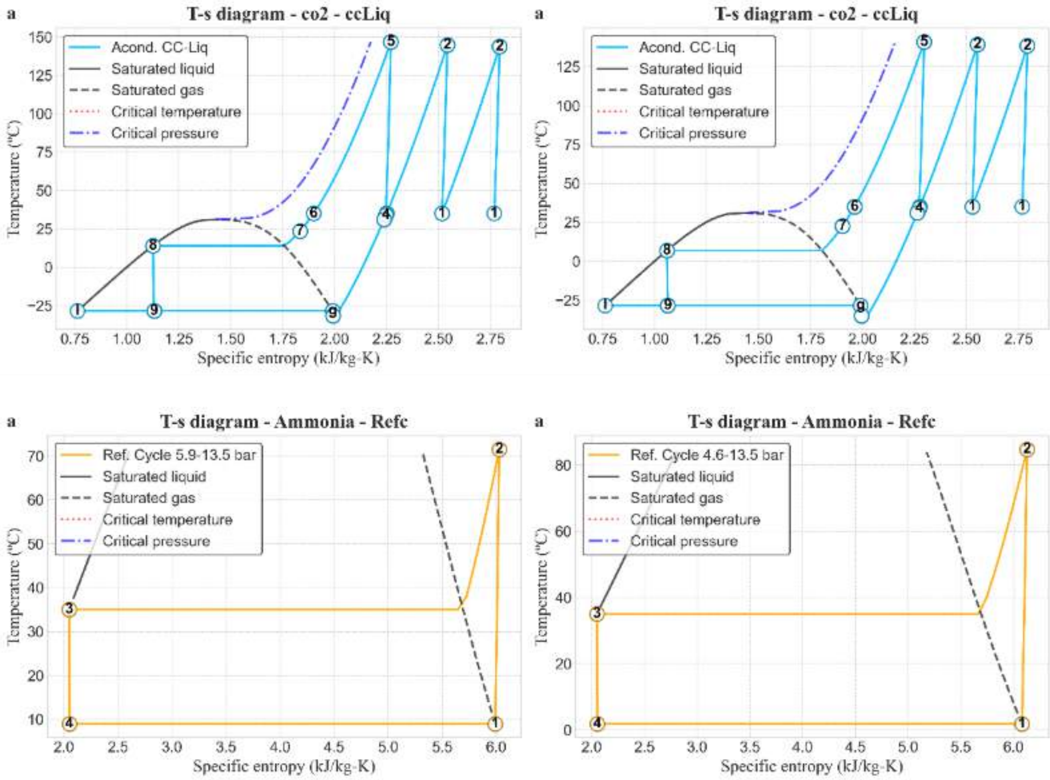

Figure 49 - Diagrams: up-left) CO2 conditioning with a 10% reduction in mixing pressure; down-left) NH3 compression refrigeration cycle with a 10% reduction in mixing pressure; up-right) CO2 conditioning with a 20% reduction in mixing pressure; down-right) NH3 compression

Reducing the mixing pressure in the CO_2 conditioning process shifts the equilibrium point towards lower temperature zones, forcing the external refrigeration cycle to adapt to maintain heat transfer.

This pressure reduction benefits the CO_2 cycle by requiring less effort from the main compressors (points 1-2, 1*-2*, 4-5). However, it penalises the ammonia cycle, which must operate with a much higher compression ratio (from 4.6 bar up to 13.5 bar) to reject heat into the environment, potentially reducing the overall system efficiency.

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	No pressure reduction			10% reduction			20% reduction		
Equipment	**Flow rate (kg/s)**	**Power (kW)**	**Outlet**	**Flow rate (kg/s)**	**Power (kW)**	**Outlet**	**Flow rate (kg/s)**	**Power (kW)**	**Outlet**
Comp A (01)	27.78	-2838.78	3.87b	27.78	-2712.90	3.67	27.78	-2573.74	3.46b
Cooler A (01)	27.78	-2908.56	35C	27.78	-2777.80	35C	27.78	-2633.49	35C
Comp A (02)	27.78	-2799.58	15b	27.78	-2678.08	13.5	27.78	-2543.36	12b
Cooler A (02)	27.78	-3085.71	35C	27.78	-2928.90	35C	27.78	-2759.67	35C
Comp B	43.27	-4099.42	58.1b	39.71	-3626.98	49.6	36.80	-3217.01	41.6b
Cooler B	43.27	-6457.78	35C	39.71	-5284.08	35C	36.80	-4390.44	35C
Rec hot	43.27	-942.51	25.5C	39.71	-786.02	23.4C	36.80	-643.30	22.6C
Rec cold	15.49	942.51	31C	11.93	786.02	31C	9.03	643.30	31C
Refrigeration	43.27	-7184.89	20.6C	39.71	-8080.75	13.9C	36.81	-8722.38	6.8C
Main exp	43.27	600.78	15b	39.71	404.04	15	36.81	260.66	15b
Sec. Exp	15.49	0	15b	11.93	42.33	13.5	9.03	67.41	12b
Refc Comp	6.45	-582.04	13.5b	7.27	-919.47	13.5	7.88	-1329.32	13.5b
Refc Exp	6.45	23.14	7.43b	7.27	43.45	5.9	7.88	72.67	4.59b
Refc Cond	6.45	-7743.79	35C	7.27	-8956.77	35C	7.88	-9979.03	35C
Refc Evap	6.45	7184.89	15.6C	7.27	8080.75	8.9C	7.88	8722.37	1.81C

Table 38 - Energy balance for the three considered cases: 0-20%. (Note: Green: effective power equipment (kW) with outlet in bar (b); Grey: non-effective power equipment (kW) with outlet in bar (b); Blue (cooling) and Orange (heating): heat exchangers (kWth) with outlet in ºC

The reduction of mixing (condensation) pressure alters the system's power balance, shifting the energy load from the process compressors to the external refrigeration system. While the CO_2 process becomes more efficient (lower compression ratio and reduction in recirculated mass flow), the ammonia cycle must perform greater work (higher compression ratio and increased mass flow) to reach lower evaporation temperatures.

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		Comp A (01)	Comp A (02)	Comp B	Refc Comp	Total Comp		Refrig.
0%	Power (kW)	-2838.78	-2799.58	-4099.42	-582.04	-10319.82	Th Power	-7184.9
	Pref (bar)	3.87 bar	15 bar	58.1	7.43		Temp (C)	20.6
10%	Power (kW)	-2712.9	-2678.08	-3626.98	-919.47	-9937.43	Th Power	-8080.7
	Pref (bar)	3.67	13.5	49.6	5.9		Temp (C)	13.9
20%	Power (kW)	-2573.74	-2543.36	-3217.01	-1329.32	-9663.43	Th Power	-8722.3
	Pref (bar)	3.46	12	41.6	4.59		Temp (C)	6.8
30%	Power (kW)	-2417.95	-2392.07	-2838.22	-1828.94	-9477.18	Th Power	-9210.3
	Pref (bar)	3.24	10.5	34.02	3.42		Temp (C)	-0.9
40%	Power (kW)	-2240.69	-2219.35	-2473.8	-2445.87	-9379.71	Th Power	-9594.1
	Pref (bar)	3	9	27	2.43		Temp (C)	-9.3
45%	Power (kW)	-2141.85	-2122.79	-2293.01	-2811	-9368.65	Th Power	-9756.5
	Pref (bar)	2.87	8.25	23.69	1.99		Temp (C)	-13.8

Table 39 - Compression consumption, refrigeration energy demand, and CO2 condensation temperature as a function of mixing pressure reduction

When analysing the complete chain (CO_2 conditioning + ammonia cycle), it is observed that the savings obtained in the main compressors compensate for the increase in refrigeration expenditure. Although the power continues to decrease, the rate of saving slows down drastically after a 30% reduction. As pressure is lowered, the temperature required to liquefy the gas drops aggressively.

Although the lowest total consumption is achieved with a 45% reduction, the resulting CO_2 condensation temperature of -13.8 °C places extreme demands on the design of the heat exchangers.

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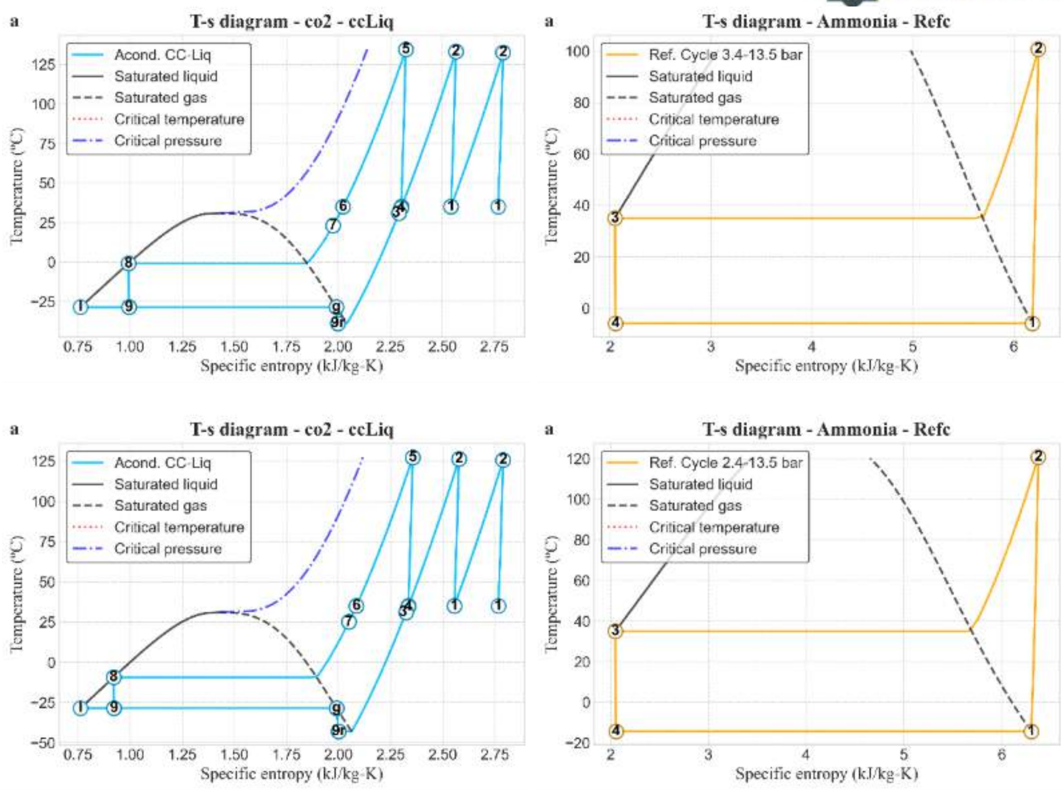

Figure 50 - Diagrams: up-left) CO2 conditioning with a 30% reduction in mixing pressure; down-left) NH3 compression refrigeration cycle with a 30% reduction in mixing pressure; up-right) CO2 conditioning with a 40% reduction in mixing pressure; down-right) NH3 compression

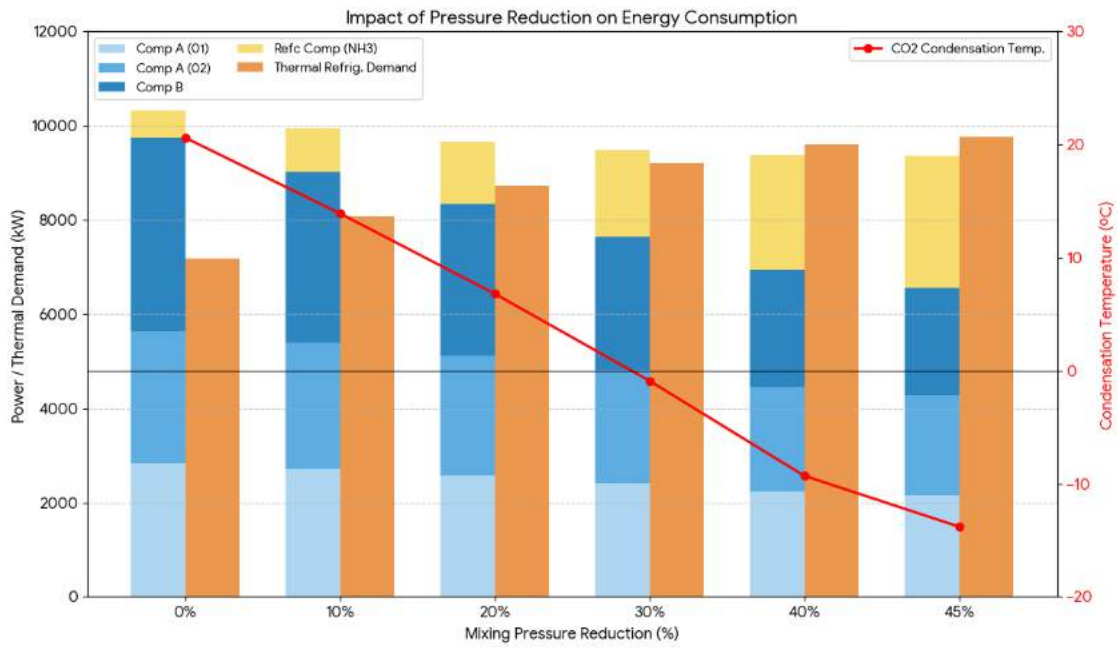

Figure 51 - Impact of pressure reduction on energy consumption

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12. Annex 3 – Risk register for the Lusitanian basin pilot

Risk ID	Risk description	Category	Likelihood	Impact	GD1 classification	Control domain	Key mitigation
R1p	Leakage through operation well	Containment	Very low	Very high	Not significant	Project-controlled	Ensure well integrity through CO_2-compatible design, qualified cementing and verification by baseline and end-of-operation CBL/USIT logging, supported by continuous monitoring of pressure, temperature and annulus conditions.
R2p	Leakage through abandoned well	Containment	Very low	Very low	Not significant	Project-controlled	Perform integrity assessment of legacy wells, including verification of abandonment status, combined with targeted monitoring to detect potential leakage pathways.
R3p	Leakage through caprock due to pressure build up	Containment	Very low	High	Not significant	Project-controlled	Control injection pressure within conservative limits and verify well integrity through continuous monitoring (DAS, pressure, temperature and annulus) and periodic logging where required.
R4p	Leakage through caprock due to poor geologic characteristics	Containment	Very low	High	Not significant	Project-controlled	Monitor plume evolution using DAS and seabed monitoring systems, with specific focus on areas surrounding legacy wells and baseline comparison.
R5p	Leakage through faults	Containment	Very low	Very low	Not significant	Project-controlled	Apply pressure management strategy including injection-rate control and predefined operational thresholds, supported by continuous monitoring and model updates.
R6p	Leakage due to natural seismicity	Operational	Very low	Low	Not significant	Project-controlled	Monitor seismicity using a Traffic Light System and apply operational thresholds to control injection in response to detected events.

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R7p	Induced seismicity	Operational	Very low	Low	Not significant	Project-controlled	Implement continuous seismic monitoring and Traffic Light System to ensure induced seismicity remains within acceptable limits.
R8p	Chemical interaction of CO_2 with seal	Containment	Low	Very low	Not significant	Project-controlled	Assess CO_2–rock interactions through laboratory testing and monitor sealing behaviour using geochemical and pressure data.
R9p	Injectivity below expectations	Injectivity	Medium	Very low	Not significant	Project-controlled	Conduct well testing and maintain operational flexibility to adapt injection rates based on observed injectivity performance.
R10p	Injectivity loss	Injectivity	medium	Low	Not significant	Project-controlled	Monitor injectivity continuously and apply corrective operational measures in case of decline.
R11p	Storage capacity below expectations	Storage Cap.	Very low	Very low	Not significant	Project-controlled	Validate storage capacity through modelling and monitoring, and adapt injection strategy if required.
R12	CO_2 accumulation in a secondary reservoir following unexpected vertical migration	Safety	Very low	High	Not significant	Project-controlled	Monitor plume evolution and pressure behaviour to detect unexpected vertical migration, supported by model updating and operational control.
R13	Slow rate of CO_2 trapping in the reservoir	Containment	Low	Very low	Not significant	Project-controlled	Validate trapping processes through monitoring and comparison with reservoir model predictions.
R14	Insufficient/ineffective monitoring during storage	Containment	Low	Medium	Not significant	Project-controlled	Ensure effectiveness of monitoring systems through redundancy, calibration and periodic verification of MMV performance.
R15	CO_2 plume exceeds expected lateral extent, leading to non-	Containment	Low	High	Significant	Project-controlled	Track plume extent using integrated monitoring (DAS, seabed systems and modelling) and adjust injection strategy if deviations are observed.

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	anticipated spill points or leakage paths						
R16	Migration of formation brine outside expected area	Containment	Very low	Very low	Not significant	Project-controlled	Monitor brine migration through pressure and geochemical data and verify that displacement remains within expected limits.
R17	Reservoir over-pressurization due to unexpected compartmentalization	Containment	Low	Medium	Not significant	Project-controlled	Detect and manage reservoir compartmentalisation through pressure monitoring and continuous updating of the dynamic model.
R18	Pilot costs higher than estimated	Economical	High	Medium	Significant	Project-controlled	Implement cost control measures including contingency budgeting, phased implementation and continuous monitoring of expenditures.
R19	Reduced injection capacity / lower well efficiency than expected	Injectivity	Medium	Low	Not significant	Project-controlled	Monitor operational performance and adjust injection strategy to maintain expected efficiency.
R20	Precipitation effect around wellbore	Injectivity	Medium	Low	Not significant	Project-controlled	Monitor wellbore conditions and manage chemical effects through operational control and fluid compatibility assessment.
R21	Flow modifications in surrounding formations	Injectivity	Very high	Very low	Not significant	Project-controlled	Monitor flow behaviour in surrounding formations and validate predictions through modelling and pressure data.
R22	Disruption by a later activity	Legal & Gov.	Very low	Medium	Not significant	External / system-level	Coordinate with other subsurface activities through regulatory engagement and spatial planning to avoid interference.
R23	Public resistance to the project	Legal & Gov.	Medium	High	Significant	External / system-level	Implement a structured stakeholder engagement and communication plan to address public concerns and maintain social licence.

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R24	Lack of political will to implement the CCS project	Legal & Gov.	Medium	High	Significant	External / system-level	Ensure alignment with policy and regulatory framework through continuous institutional engagement.
R25	CO_2–seal/fault rock interaction	Operational	Low	Very low	Not significant	Project-controlled	Monitor CO_2 interaction with materials and ensure compatibility through appropriate design and operational control.
R26	CO_2 plume extent exceeds expectations and interacts with other subsurface resources	Operational	Very low	Very low	Not significant	Project-controlled	Monitor plume extent and ensure no interaction with other subsurface resources through modelling and MMV.
R27	Unexpected seabed risks	Operational	Very low	Low	Not significant	Project-controlled	Establish baseline seabed conditions and perform repeat surveys to detect and assess unexpected seabed risks.
R28	Damage to the wellhead, leading to a leak or shutdown.	Operational	Very low	High	Significant	Project-controlled	Ensure robustness of wellhead design and implement operational procedures and safety systems to prevent damage and enable rapid shutdown.
R29	Failure to ensure CO_2 is in supercritical phase in the reservoir	Operational	Very low	Low	Not significant	Project-controlled	Maintain CO_2 in dense phase through control of injection pressure and temperature conditions.
R30	Simultaneous operations interference	Operational	Medium	Low	Not significant	Project-controlled	Plan and coordinate simultaneous operations to minimise operational interference.
R31	Drilling window missed or rig unavailability	Operational	Medium	Medium	Not significant	Project-controlled	Mitigate drilling risks through early planning, contractor engagement and scheduling flexibility.
R32	Disruption of other uses in the area due to the CO_2 pilot	Operational	Very high	Low	Not significant	Project-controlled	Coordinate with other offshore users and manage interactions through operational planning.

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R33	Infrastructure damage from natural seismicity	Operational	Very low	High	Significant	Project-controlled	Monitor seismicity and apply operational thresholds and design criteria to prevent infrastructure damage.
R34	CO_2 interaction with well cement and materials	Operational	Very low	Low	Not significant	Project-controlled	Ensure material compatibility and monitor well integrity to prevent degradation due to CO_2 exposure.
R35	NOx deposition in natural areas	Operational	Very low	Low	Not significant	Project-controlled	Monitor emissions and apply environmental control measures to limit impacts.
R36	Restrictions to fishing activities around the well location	Social	Very high	Medium	Significant	External / system-level	Engage with fisheries and maritime stakeholders to manage access restrictions and minimise conflicts.
R37	Impact on touristic activities due to the pilot operations	Social	Medium	Low	Not significant	External / system-level	Engage with local stakeholders to manage impacts on tourism and public perception.
R38	Loss of employment in other sectors	Social	Very low	Very low	Not significant	External / system-level	Monitor socio-economic impacts and maintain communication with affected sectors.
R39	Permeability degradation during injection due to chemical/mineral precipitation in the reservoir	Storage Cap.	Medium	Low	Not significant	Project-controlled	Monitor reservoir performance and manage permeability changes through operational control.
R40	Undetected flow barriers in the reservoir	Storage Cap.	Low	Medium	Not significant	Project-controlled	Detect flow barriers through monitoring and well testing and update reservoir model accordingly.
R41	Low average permeability	Storage Cap.	Medium	Very low	Not significant	Project-controlled	Validate reservoir properties through testing and modelling to ensure performance assumptions.

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R42	Lack of financial incentives or changes in CO_2 pricing	E-Economical	Medium	High	Significant	External / system-level	Address financial risks through alignment with policy frameworks and contingency planning.
R43	Uncertainty in CO_2 supply sources	E-Economical	High	High	Significant	External / system-level	Secure CO_2 supply through agreements and diversification of sources.
R44	Diificulties in access to subsidies / incentives / funding	E-Economical	Medium	High	Significant	External / system-level	Mitigate funding risks through financial planning and access to subsidies or incentives.
R45	Uncertainty in CCS policy support or unexpected regulatory changes	P-Political	Medium	High	Significant	External / system-level	Monitor regulatory developments and adapt project planning accordingly.
R46	Delays or inability to obtain key permits	P-Political	Medium	Medium	Significant	External / system-level	Implement structured permitting strategy and early engagement with competent authorities.
R47	Local authority opposition despite national-level support	P-Political	Low	Low	Not significant	External / system-level	Engage local authorities and stakeholders to ensure alignment across governance levels.
R48	Competitor securing acreage before PilotStrategy (first-mover disadvantage)	L-Legal	Very low	Medium	Not significant	External / system-level	Monitor competitive environment and maintain project positioning through strategic planning.
R49	Social fragmentation/ polarization	S-Social	Medium	Low	Not significant	External / system-level	Address social fragmentation through proactive stakeholder engagement and communication.

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