WP4 -Deliverable 4.11

Description and results of the probabilistic assessment and sensitivity analysis of the development concept

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1. Document History

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1.2 Revision History

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1.4 Distribution

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2. Executive summary

Work package 4 of PilotSTRATEGY aims to assess and compare optimal development concepts for CO_2 storage pilot projects in the Paris Basin (France), Lusitanian Basin (Portugal), and Ebro Basin (Spain), supporting decisions on their technical and commercial viability within environmental, social, and regulatory constraints. In parallel, it enhances understanding of CO_2 storage opportunities in Western Macedonia (Greece) and Upper Silesia (Poland). Task 4.4 focuses on the economic feasibility of the selected development concepts, recognizing the high geological, technical, and financial uncertainties at this stage. The economic evaluation is therefore conducted in two steps: first, a deterministic, simplified comparative assessment for all regions to prioritize alternatives and select an optimal pilot concept (Deliverable 4.9); and second, a detailed probabilistic economic evaluation for the main regions (France, Portugal, and Spain), integrating subsurface uncertainties and results from WP3, presented in this report (Deliverable 4.11). Probabilistic analysis supports informed decision-making by explicitly addressing risks and uncertainties rather than predicting exact outcomes. The evaluated development concepts are based on definitions provided in Deliverable 4.5 and Milestone 4.3, which describe optimized technical solutions for CO_2 capture, transport, and injection. Although each region conducts its assessment independently, a common methodology and economic framework are applied, resulting in a consistent technical description, economic evaluation, conclusions, and recommendations for each proposed pilot scenario.

The economic evaluation highlights distinct regional outcomes driven by infrastructure maturity, storage capacity, and market conditions. In the **Paris Basin (France)**, scenarios based on externally sourced CO_2 are generally more attractive than local capture thanks to lower compressor CAPEX, although market availability of external CO_2 remains a limiting factor; cost uncertainties allow for limited probability ranges where local options may prevail. The **Lusitanian Basin (Portugal)** pilot exhibits a high-cost, low-revenue profile typical of early offshore demonstrations, with total expenditures around €100 million and wide uncertainty, positioning the project primarily as a strategic learning and de-risking investment for future commercial CCS scale-up. In the **Ebro Basin (Spain)**, storage capacity is the dominant economic driver, with positive NPVs under EU ETS conditions across all cases; upside capacity scenarios significantly improve viability, while break-even storage fees may constrain commercial development at lower capacities.

As well, Poland and Greece have presented a simplified economic assessment. In **Poland**, the absence of CO_2 transport infrastructure and limited CCS experience concentrate financial risk in the pre-investment phase, suggesting that pilot deployment is best supported by public research and innovation funding until higher carbon prices and scale effects materialize. Finally, **Western Macedonia (Greece)** shows strong economic potential, targeting 90 Mt of storage with CAPEX of €301 million plus contingency and an estimated NPV of €991 million under conservative assumptions, supported by long-term injection, dedicated CO_2 pipelines, and opportunities for local CO_2 utilization to enhance cost efficiency and revenues.

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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. The objective of the WP4 is to provide and analyse available information of the optimum development concept applicable to the proposed pilots of the Paris Basin (FR), the Lusitanian Basin (PT), and the Ebro Basin (ES) to go ahead with the decision of whether these pilots are viable technically and commercially, considering social and environmental demands, and in the existing European and local regulatory frame. It will also enhance the knowledge of CO_2 storage options in the Western Macedonia region (GR) and Upper Silesia region (PL).

The *Task 4.4: Economic evaluation of selected concept scenarios and prioritization of opportunities* is focus on the economic feasibility of proposed pilots' development for each region and, at this stage, geological, technical and financial knowledge presents high uncertainties which must be managed and evaluated. For this reason, the economic evaluation have been carried out in two steps: (1) For each region (FR, PT, ES, GR, PL) an alternative-compared evaluation for each selected pilot, based on simplified models, with a deterministic approach, presented in the **Deliverable 4.9** (Canteli, 2025b), to prioritize the alternatives defined for each region based on this economic evaluation, and selection of an optimum pilot development; and (2) For this selected pilot development, a detailed economic evaluation for the main regions (FR, PT, ES) considering probabilistic-economic evaluation, including subsurface uncertainties according to WP3 results (modelling and dynamic simulation), and presented in this **Deliverable 4.11.**

A probabilistic economic evaluation is crucial to decision makers (policy-makers, scientists, engineers and potential investors, between others) as it brings the opportunity to integrate results from previous WPs works (estimated volumetric capacity, facilities development, MMV plan, time planning, costs) and their uncertainties, and evaluate the impact of them in economic terms. Probabilistic analysis should not be seen as a tool to make accurate predictions about future: this approach should be understood as facilitator to understand and discuss risks and uncertainties to make informed and strategic decisions.

The optimum development concept evaluated by each region has been described on **Deliverable 4.5** *From capture to the injection facilities definition: capture, transport and CO2 stream quality* (Lachen *et al.,* 2025). Its purpose was to define the key technical elements for the development of pilot projects for CO_2 capture, transport, and injection, for the development concept selected -pilot or commercial scale-up. As well, in more detail, selected concept development was presented by each region on the **Milestone 4.3** *Presentation of a feasible optimized pilot design* (October 2025), which are briefly described for each region to easy follow up.

This work is carried out by each region independently, although following the same methodology and under the same economic evaluation frame. As a result, each region will:

- Describe technically proposed developments (scenarios).
- Carry out their economic evaluation.
- Present their results.
- Conclusions and recommendations.

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A technical description of a scenario, in this context, refers to an overview of elements to build and activities to carry out along the time for building a pilot. The technical elements to be included (transport type, surface facilities, injector wells, storage volumes…) are aligned with the key decision defined during the framing session and included in the scenario's definition.

4. Common economic frame and approach

Even though a comparison between regions won´t be part of this work, it was agreed to define a common economical frame and approach to carry out the economic evaluation to facilitate assessment, exchange of results, and recommendations. As well, all cases are focused on a storage site operator evaluation (that is, no capture costs are included). The economic results will be presented for key percentiles: 10th percentile (P10), 50th percentile or median (P50), 90th percentile (P90) as illustrated in Figure 4.1 below:

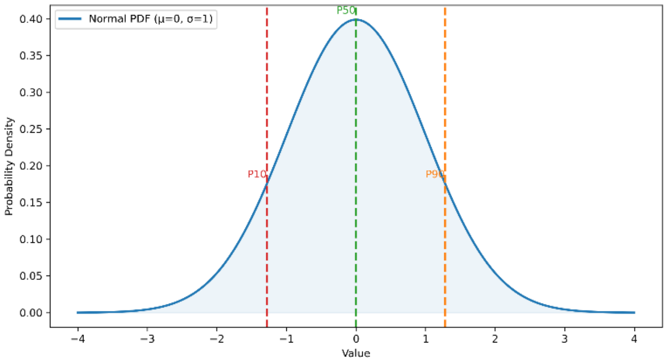


Figure 4.1 typical percentiles of a normal distribution!

The common economic parameters are:

- **Year of reference**: 2025
- **Starting year**: 2027
- Economic evaluation based on **discounted and inflated cashflow**, when it is possible (if commercial development is considered). In other case, **discounted and inflated costs**. Income/positive from **stored** CO_2 based on at **ETS market price forecast**.
- **Cost estimate**: Class IV of the Cost Estimate Classification System[1]: range of accuracy -30% to +50%
- **Discounted rate**: 9%[2]
- **Inflation rate**: 2.2%[3]
- **Currency**: Euros. Exchange rate for other currency at first working day of September 2024. (i.e. 2nd September 2024). For reference, 1 USD=0.9041 €[4]

[1] https://www.processengineer.com/insights/capital-cost-estimate-classes

[2] Discount rate of firms in energy demand sectors. Non—energy intensive industries. EU Reference Scenario 2020. Energy, transport and GHG emissions - Trends to 2050. (ISBN 978-92-76-39356-6)

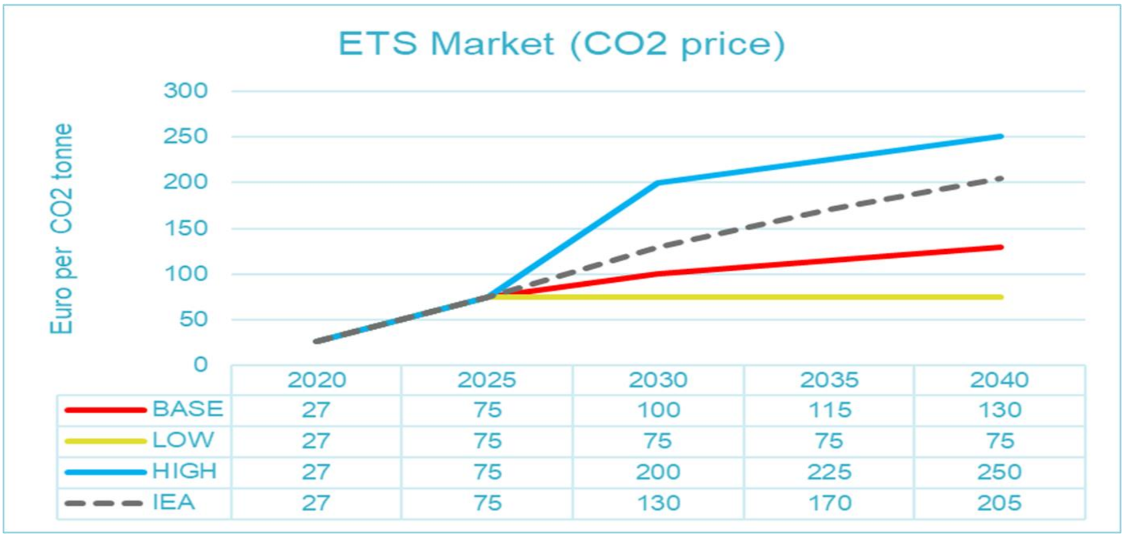
[3] Inflation dashboard and available data series for August 2024 of European Central Bank. Overall index for Euro area. https://www.ecb.europa.eu/stats/macroeconomic_and_sectoral/hicp/more/html/data.en.html

[4] https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-

- CO_2 **price forecast (ETS market** forecast): Defined Base price (75 €/t @2025; 100 €/t @2030; 115 €/t @2035; 130 €/t @2040 and thereafter) for economic evaluation and Low and High prices for sensitivity analysis. Compared with available international organization forecasts (IEA (2019)[5], Enerdata[6], Bloomberg[7]) proposed base price is more conservative but all of them are covered by proposed sensitivity analysis range.

- **Electricity price:** Following "industry profile" included in European Electricity markets Q4 2024 report[8] (average electricity prices before taxes in €(2015)/MWh). Despite this model is from 2015, current electricity markets are coming back to pre-pandemic values, and it is expected to decline more due to the renewable increase impact. (electricity price: 75 €/MWh @2025; 85 €/MWh @2030; 89.3 €/MWh @ 2040; 98.4 €/MWh @ 2050 and thereafter).
- **To bring cost from earlier years to 2025** (for example, well cost@2020 to 2030), it can be applied one of these options (the same for the different cases):
  - Apply a recognized update cost index until 2024, and 2.2%/year thereafter.
  - Apply an average inflation rate from cost year until 2024, and 2.2%/year thereafter.
  - Apply 2.2 %/year from cost year to cost application year.

- **Costs Contingency:** +20% except other case is considered.



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

Figure 4.2 CO_2 price forecast from 2025 to 2040 and thereafter and comparison with IEA proposal (2019).

usd.en.html#:~:text=Analyse%20the%20results.%20Download%20XML%20(SDMX)%20RSS%20feed%20with%20daily

[5] https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf

[6] Carbon Price Forecast 2030-2050: Assessing Market Stability & Future Challenges | Enerdata

[7] Global Carbon Market Outlook 2024 | BloombergNEF (bnef.com)

[8] https://energy.ec.europa.eu/document/download/edb2e73e-c0df-4aa1-abdb-fd8eac1d1799_en?filename=Quarterly%20Report%20on%20European%20Electricity%20markets%20Q1%202024.pdf

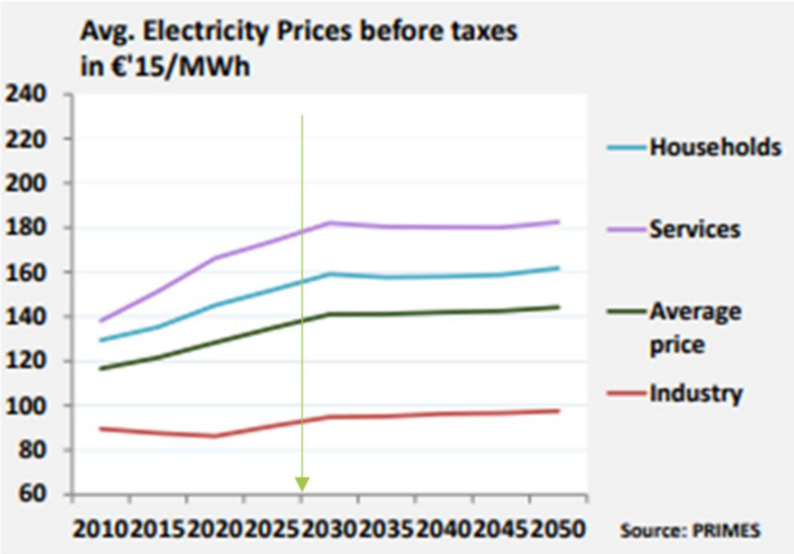


Figure 4.3 Electricity price by sector. Proposed industry profile for techno-economic evaluation (source: European Electricity Market[7])

5. Probabilistic assessment of the development concept by regions

A probabilistic economic evaluation supports informed decision-making by integrating technical and economic results with their uncertainties. It combines outputs from previous work packages, including capacity estimates, infrastructure, planning, and costs. Rather than providing precise forecasts, it helps frame and quantify risks. This approach facilitates strategic discussions and robust decision-making under uncertainty.

5.1 Paris Basin (France)

The French case 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 almost pure CO_2 to be qualified as a pilot under the CCS directive–2009/31/EC[9].

5.1.1 Description of the scenarios

The case is based upon the outlet stream of the emitter from a Steam Methane Reformer with a composition of 99% CO_2 and 1% H_2 (D4.9 - Canteli et al, 2025b). The main source is associated with ammonia production plant process via natural gas reforming. Due to the evolution of the industrial strategy of the plant publicly announced in early 2025, an alternative scenario is considered in which the CO_2 is transported by train to the plant location. The external source of CO_2 is not identified within the project. Therefore, the project considers four scenarios as illustrated in Figure 5.1:

- different wellhead locations: offsite – onsite following exchanges with local stakeholders
- different CO_2 sources: local – external

[9] https://eur-lex.europa.eu/eli/dir/2009/31/oj/eng

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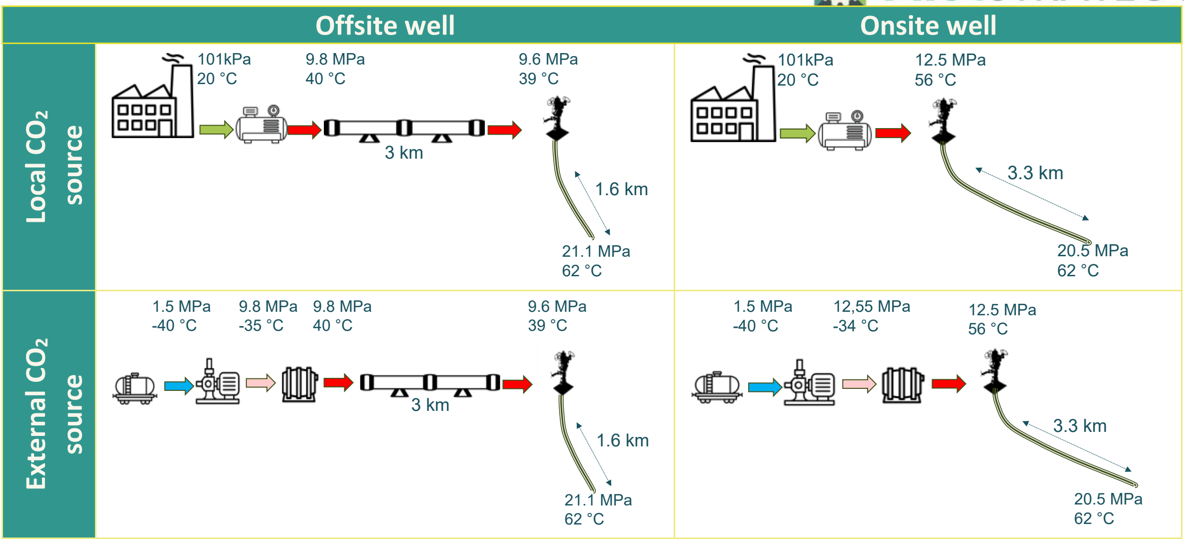

Figure 5.1 Development scenarios considered for a CO_2 injection pilot project in Paris Basin

The technical specifications of the various equipment (pipeline, well, compression…) are detailed in D4.5 (Lachen *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.

As shown in Figure 5.1, the main scenario for detailed dimensioning studies includes the following equipment:

- Compression with or without a pipeline between the emitter site and the well head
- Injection well with different inclinations and lengths to reach the target in the storage formation

For the alternate scenario shown in Figure 5.1, CO_2 arrives by train and the detailed dimensioning studies includes the following equipment:

- Unloading equipment, pump and heater with or without a pipeline between the emitter site and the well head
- Injection well with different inclinations and lengths to reach the target in the storage formation

5.1.2 Proposed planning

Following the monitoring strategy developed in D4.6 (Canteli *et al.*, 2026), a possible planning for the whole pilot injection was elaborated and recalled in Figure 5.2 while assuming a theoretical start of the project with filing to the request for an exploration permit review in 2027 as assumed in section 4. As assumed in Figure 5.2, the injection would take place in 2032, and the post-injection monitoring would last 8 years up to 2039 when the CO_2 will no longer be migrating. As assumed in Figure 5.2, the main steps during the CO_2 pilot life cycle would be:

- 2027-2028: Review of the pilot permit request by the administration
- 2029-2031: Construction phase (injection well, CO_2 plant with/without pipeline) and baseline monitoring

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- 2032: CO_2 injection at commercial rate (0.3 Mtpa) during 3 months to limited to 100kt with pressure and CO_2 plume monitoring
- 2033-2039: CO_2 plume monitoring
- 2040: dismantling of the equipment according to regulatory requirements.

The technical description of these steps is in D4.6 (Canteli *et al.*, 2026).

The cost estimates do not include uncertainties due to delays in implementation of the proposed planning.

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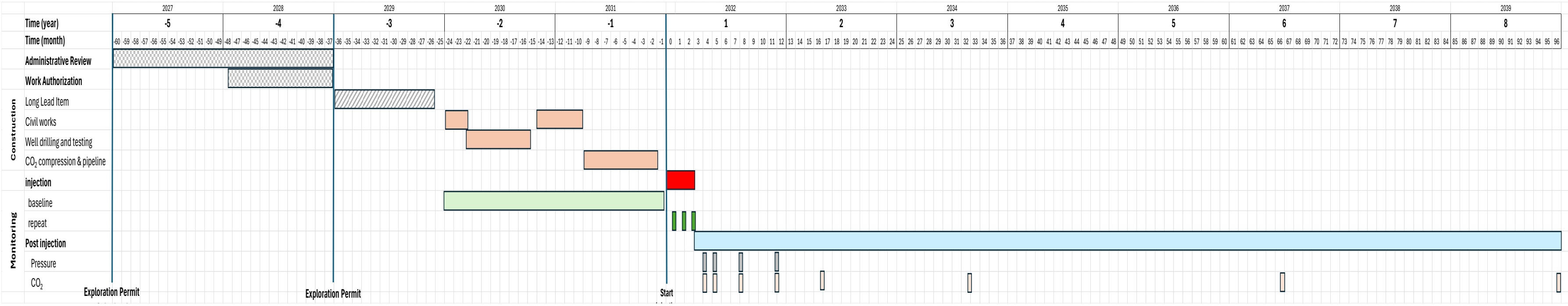

Figure 5.2: Foreseen life cycle planning for a CO_2 injection pilot from administrative filing to post-injection monitoring.

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5.1.3 Description of the main cost assumptions

All the reported costs are escalated for inflation and converted to current euros (€$_{2025}$) as defined in section 4. The uncertainties on cost estimates are Class IV which are mostly obtained from technology providers based upon the 2025 French market conditions, but they may significantly vary due to the evolution of the oil and gas market services.

5.1.3.1 *CO_2 conditioning plant cost*

The CO_2 conditioning plant design is detailed in D4.6 (Canteli et al., 2026).

5.1.3.1.1 Local CO_2

CAPEX

At this conceptual / feasibility study stage, the Surface Facilities CAPEX estimation (Figure 5.3) is based on factorization on equipment and parametric model, with in-house data. The capital cost (CAPEX) for the Engineering, Procurement and Construction (EPC) comprises of all the expenditures associated with the primary creation of the specific plant or facility: this usually embraces the following described direct and indirect construction and engineering related elements.

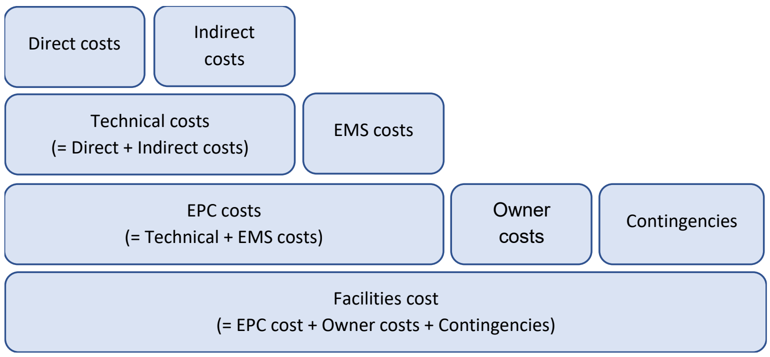

Figure 5.3: Surface facilities CAPEX breakdown structure

Technical costs (Direct costs + Indirect Costs) are evaluated with the following philosophy:

- Process blocks (system or unit) identification and main components (process equipment) characteristics definition.
- Main equipment Ex-Works cost estimation by scaling factors (Chilton's factors or equivalent from *cost estimating - compass international 2021*).
- Main equipment related Direct + Indirect costs estimation by Lang's factors or equivalent from *cost estimating - compass international 2021*: it will cover related bulk material procurement, associated construction costs, allowances, general permanent facilities and infrastructure, interconnections, spare parts (capital spare parts, commissioning spare parts), transportation, logistical support, temporary construction facilities.

Engineering Management Services (EMS) are evaluated as a percentage of Technical Costs. They cover:

- Detailed Engineering,
- Procurement, purchasing, sub-contracting,
- Contractor management,
- Site supervision,

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- Assistance to plant commissioning and start-up.

Owner (Company) costs are excluded from the present model, except for Basic Engineering / FEED (Front End Engineering Design) and Project Management Consultant (PMC). They are listed in the Cost Exclusion list in dedicated chapter.

Contingencies are usually evaluated at about 20 to 25% of the above costs and are added on top of the estimate to complete the facilities cost (Technical costs + EMS + Owner costs) instead of being allocated to the sections previously defined. Contingencies cater for uncertainties in the estimate which are likely to occur, but which cannot be specifically identified at the time the estimate is prepared. Contingencies cater for:

- Errors of the estimation model,
- Uncertainties on unit costs,
- Uncertainties on quantities,
- Possible variations of the workforce,
- Variations of productivity,
- Risks associated to the selected process,
- Minor changes of design.

The following costs are excluded from the CAPEX model:

- Owner (Company) costs: Surveys, Insurances, Certification and expertise, Ready for start-up activities, Land acquisition, right of way, taxes, customs duties, harbor fees
- CO_2 supply and production facilities,
- Mutualized installations with the existing plant such as control room, administration building, warehouse, gate building, firefighting facilities, parking for trucks, new railways, etc.
- Two-year spare parts (included in OPEX). However, commissioning & start-up spare parts, Ready for Start-Up (RFSU) and Start-Up (SU) costs are included in the estimate.
- Pre-operation costs (training of operators, first fill of chemical products, etc.)
- Raw materials price fluctuations,
- Finance fees,
- General expenses of local operating subsidiaries,
- Risks covered by insurances,
- Management Reserve: amount added to an estimate to allow for discretionary management purposes outside of the defined scope of the project, as otherwise estimated,
- Change in scope or in Basis of design, process design modifications, major market effects, lack of competition, major risks, Force Majeure cases.
- Special civil works.

Various design options evaluated are:

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Offsite case: The injection well head is located 3 km from the CO_2 collection point. The CO_2 gas plant which includes one compressor unit, air cooler and its utilities, will be installed within the existing plant. A new 3 km, 6'' carbon steel underground pipeline will connect the two installations.

Onsite case: The injection well head is located within the existing plant, adjacent to the CO_2 collection point. The CO_2 gas plant which includes one compressor unit air cooler, and its utilities will be installed nearby, with a surface piping system connecting the two installations.

Component	P10	P50	P90
CO_2 plant offsite	34.45	43.28	52.27
CO_2 plant onsite	34.73	42.40	51.20

Table 5.1 Distribution of the CAPEX (M€$_{2025}$) for the conditioning plant for local CO_2

OPEX

The three major operating and maintenance costs components for underground storage facilities are:

- Labour – Plant operation personnel,
- Maintenance surface,
- Maintenance subsurface (if any),
- Consumable (especially Fuel and energy consumption).

The operations are planned for a 3-month injection. Thus, the OPEX are estimated over 4 months to account for safety and startup verifications.

The OPEX have been estimated considering that the new CO_2 logistic facilities are integrated in existing operational plant, meaning that the current team and some utilities are shared between existing and the new activities. As a result, labour cost will be minimized.

Surface and subsurface maintenance over four months is considered negligible and can be performed by contractors already engaged by the existing plant if needed. Within this duration, it is not expected major failure of the new installations or maintenance activities (painting, etc).

Energy consumption is based on an electricity cost of 86 €/MWh (estimates for the injection planed in 2032 from section 4) and an operation for 120 days 24h/24h which represents 2 880 hours. A provision of 10% is added for other consumables and a provision of 15% is added for additional labour and maintenance.

Component	P10	P50	P90
CO_2 plant offsite	0.58	0.7	0.85
CO_2 plant onsite	0.58	0.7	0.85

Table 5.2 Distribution of the OPEX (M€$_{2025}$) for the conditioning plant for local CO_2

5.1.3.1.2 External CO_2

This case involves CO_2 discharge by rail wagons.

Offsite case: The injection well head is located 3 km from the CO_2 collection point. The CO_2 gas plant which includes two discharging skid, one tank, one cryogenic pump, one electrical heater and utilities will be installed within the existing plant. A new 3 km, 6'' carbon steel underground pipeline will connect the two installations.

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Onsite case: The injection well head is located within the existing plant, adjacent to the CO_2 collection point. The CO_2 gas plant which includes two discharging skid, one tank, one cryogenic pump, one electrical heater and utilities will be installed in the existing plant, and a surface piping system will connect the two installations.

Component	P10	P50	P90
CO_2 plant offsite	12.08	14.75	17.81
CO_2 plant onsite	11.83	14.44	17.44

Table 5.3 Distribution of the CAPEX (M€$_{2025}$) for the conditioning plant for external CO_2

5.1.3.2 CO_2 pipeline cost

As proposed in D4.6 (Canteli *et al.*, 2026), the new 3 km, 6'' carbon steel underground pipeline will connect the plant to the well-head installations for the **Offsite cases**.

Component	P10	P50	P90
CO_2 pipeline	1.33	1.62	1.96

Table 5.4 Distribution of the CAPEX (M€$_{2025}$) for the CO_2 pipeline

5.1.3.3 CO_2 well cost

The well costs include the drilling operations, the long-lead items such as well-head and Xmas tree, casings and tubing, the open-hole and cased-hole logging along to the well testing (brine injection) as described in D4.6 (Canteli *et al.*, 2026). These costs are established based upon the 2025 French market conditions but may significantly vary due to oil and gas world market over the coming years.

To estimate the costs of the two well designs, detailed estimates of the drilling equipment and operations such as civil works and noise barriers, mobilization and demobilization of the drilling rig, removal/treatment of cuttings, drilling fluids, mud logging, cementing, coring, energy requirements and logistics. Due to the different lengths and deviations of the two well designs, the costs are significatively different along with the logging programs as described in D4.6 (Canteli *et al.*, 2026).

The well CAPEX is merged in several groups:

- Civil works for the platform setup and a 50-meter pilot hole
- Long Lead Items includes line hanger, well head and Christmas tree, casing and tubing
- Drilling includes all cost during well drilling such as rig, removal/treatment of cuttings, drilling fluids, mud logging, cementing, coring, energy requirements and logistics
- Insurance mostly for the rig cost (1.5%) and Long Lead Items cost (6%) and 5% for the contingency
- Logging & testing includes fiber optics, downhole pressure and temperature gauges, cased-hole (CBL/USIT) and open-hole logs (caliper, Gamma Ray, Neutron, Density, Sonic…) and well testing.

Component	Slightly deviated well			Strongly deviated well		
	P10	P50	P90	P10	P50	P90
Civil works	1.26	1.45	1.63	1.26	1.45	1.63
Long Lead Items	1.27	1.42	1.59	1.84	2.07	2.37
Drilling	5.26	5.63	6.04	8.02	8.55	9.13
Insurance	0.68	0.78	0.89	0.89	1.02	1.17
Logging & testing	1.39	1.67	1.94	2.02	2.46	2.90

Table 5.5 Distribution of the CAPEX (M€$_{2025}$) for the CO_2 wells

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5.1.3.4 CO_2 monitoring cost

As shown in Figure 5.2, the monitoring strategy will depend upon the component of the storage complex, the technique, and the frequency. Prior to CO_2 injection, data acquisition would be required for all monitoring techniques to establish a baseline (natural background) level. During the injection period, the periodic measurements would be carried out every month while in a geometric progression during the 8-year post injection period (see D4.6 for details). Consequently, the monitoring costs need to be escalated for inflation and converted to current euros. The monitoring costs are established based upon the 2025 French market conditions but may significantly vary due to oil and gas world market over the coming years. Depending on the requirement for each monitoring technique considered (see D4.6 for details) and shown in Figure 5.4, part of the monitoring costs are considered as CAPEX e.g. micro-seismic equipment and wells while most of the monitoring costs are assumed as OPEX e.g. INSAR, water sampling, DAS-VSP.

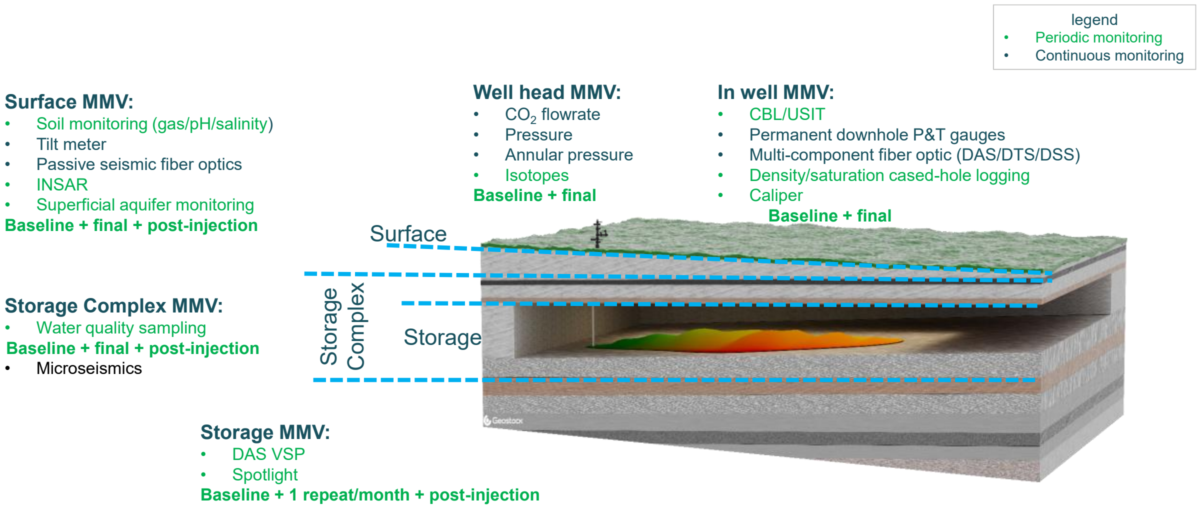

Figure 5.4 Monitoring techniques considered for a CO_2 injection pilot project in the Paris Basin (D4.6 - Canteli et al., 2026)

5.1.3.4.1 In-well monitoring

CAPEX

These monitoring techniques may be either continuous such as fiber optics, pressure and temperature gauges, or periodic such as cement logs (CBL/USIT) or electrical logs (caliper, density). Given the foreseen 3-month injection period, the periodic monitoring of the well will only be carried out at the end of injection. These costs are integrated in Table 5.5.

OPEX

Component	Slightly deviated well			Strongly deviated well		
	P10	P50	P90	P10	P50	P90
logs	0.93	1.23	1.54	1.54	2.11	2.68

Table 5.6 Distribution of the OPEX (M€$_{2025}$) for the in-well monitoring

5.1.3.4.2 Storage formation monitoring

The DAS-VSP and SpotLight™ monitoring costs were obtained from providers as indicated in D4.6. The monitoring acquisition were synchronized between the two technologies to optimize the mobilization/demobilization costs for the source (vibrator truck).

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CAPEX

No specific additional CAPEX is required

OPEX

Component	P10	P50	P90
DAS-VSP + Spotlight	2.76	3.09	3.44

Table 5.7 Distribution of the OPEX (M€$_{2025}$) for the storage monitoring

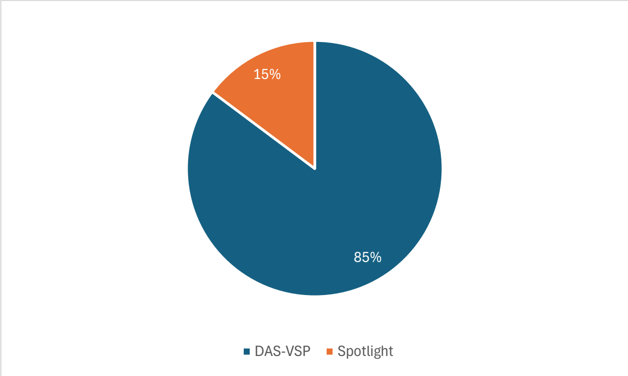

Figure 5.5 Monitoring OPEX distribution for the storage

In Figure 5.5, the Spotlight™ costs do not include the cost of the source which is incurred to the DAS-VSP.

5.1.3.4.3 Storage complex monitoring

CAPEX

The monitoring of the storage complex is proposed based upon tilt meters and micro-seismics (shallow holes and geophones with a SCADA system (Supervisory Control and Data Acquisition)) along with passive seismics acquisition equipment. Such equipment CAPEX is estimated below.

Component	P10	P50	P90
tiltmeters + micro&passive seismics	2.26	2.50	2.75

Table 5.8 Distribution of the CAPEX (M€$_{2025}$) for the storage complex monitoring

OPEX

The OPEX monitoring costs represents the yearly treatment costs associated with each technique based upon Geostock's experience.

Component	P10	P50	P90
micro&passive seismics	0.16	0.21	0.27

Table 5.8 Distribution of the OPEX (M€$_{2025}$) for the storage complex monitoring

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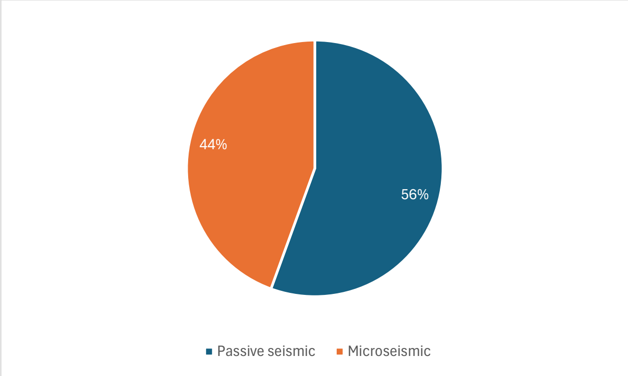

Figure 5.6 Monitoring OPEX distribution for the storage complex

5.1.3.4.4 Surface monitoring

CAPEX

No specific additional CAPEX is required

OPEX

The soil monitoring and shallow water sampling were estimated from Guinan et al (2024), the INSAR monitoring costs were estimated from public data. These costs refer to campaigns as designed in D4.6 for soil monitoring and shallow water sampling and over the study area (10 x10 km^2) for the INSAR. The costs may be different from commercial bids from providers.

Component	P10	P50	P90
Soil monitoring +INSAR +shallow water sampling	0.26	0.28	0.31

Table 5.9 Distribution of the OPEX (M€$_{2025}$) for the surface monitoring

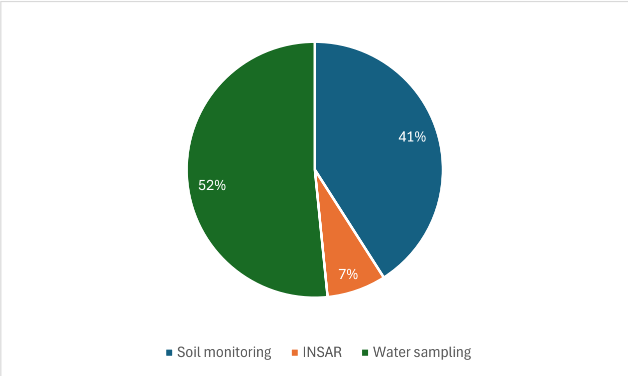

Figure 5.7 Monitoring OPEX distribution for the surface

5.1.4 Economic assessment

The distributions of the costs are assumed to be PERT distributions when the uncertainty could be estimates and uniform distributions when only a single cost values was determined.

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A PERT distribution (Program Evaluation and Review Technique distribution) is a probability distribution which is a special case of the more general Beta distribution, but specifically parameterized using three points:

- Minimum The optimistic estimate (shortest possible time or smallest value).
- Most likely: The mode (the most probable value).
- Maximum: The pessimistic estimate (longest possible time or largest value).

A PERT distribution is a continuous distribution **bounded between the minimum and maximum values**. It produces a smoother curve and better reflects uncertainty than a triangular distribution.

The modelling is performed with @Risk™ software[10] using 10^6 Monte Carlo realizations.

5.1.4.1 *CAPEX*

The pipeline and CO_2 plan costs are combined to estimate the CAPEX of the surface installations as summarized in Table 5.10. The main cost driver between local and external CO_2 scenario is the CAPEX associated with the compressor which is significantly larger than the rail wagon discharge equipment. The difference between offsite and onsite scenarios due to the CAPEX for the CO_2 pipeline.

Scenario	offsite			onsite		
	P10	P50	P90	P10	P50	P90
Local CO_2	37.09	44.91	53.90	34.73	42.40	51.20
External CO_2	13.70	16.39	19.46	11.83	14.44	17.44

Table 5.10 Distribution of the CAPEX (M€$_{2025}$) for surface installations (pipeline+ plant) for the various scenarios

The well drilling, testing and the additional costs for monitoring are combined to estimate the CAPEX of the subsurface installations as summarized in Table 5.11. The main cost driver between offsite and onsite scenarios is related to the well deviation and length which imply longer drilling time and equipment costs.

Scenario	offsite			onsite		
	P10	P50	P90	P10	P50	P90
Local CO_2	8.84	9.30	9.76	12.47	13.11	13.78
External CO_2	8.84	9.30	9.76	12.47	13.11	13.78

Table 5.11 Distribution of the CAPEX (M€$_{2025}$) for subsurface installations (well and its equipment) for the various scenarios

The previous CAPEX distributions are added together to estimate the pilot project CAPEX as summarized in Table 5.12 and illustrated in Figure 5.8

Scenario	offsite			onsite		
	P10	P50	P90	P10	P50	P90
Local CO_2	50.54	58.39	67.39	52.79	60.48	69.32
External CO_2	27.12	29.86	32.98	29.81	32.54	35.63

Table 5.12 Distribution of the CAPEX (M€$_{2025}$) for CO_2 pilot for the various scenarios

[10] https://lumivero.com/products/at-risk/ version 7.5.1

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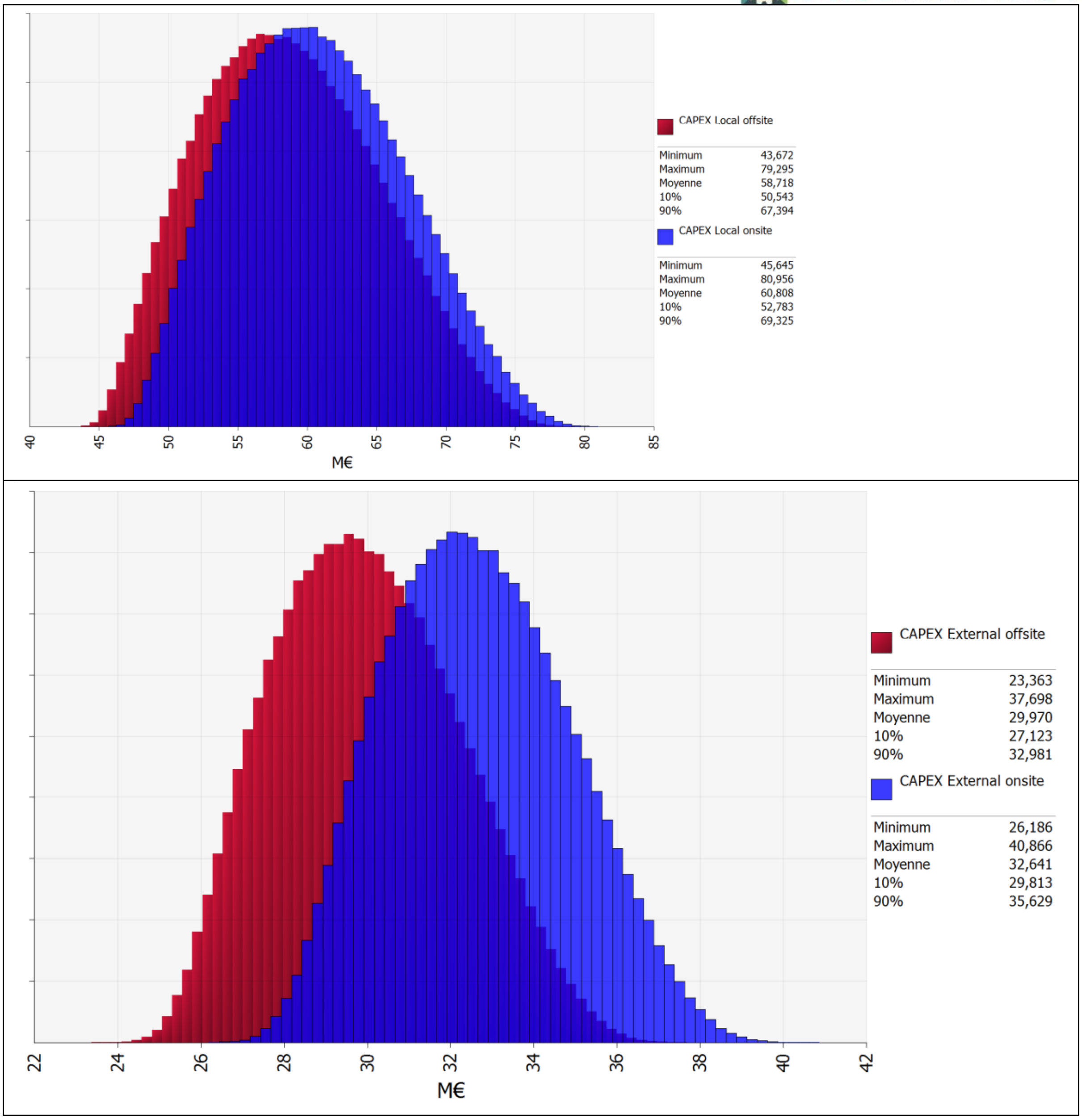

Figure 5.8 Distribution of the CAPEX (M€$_{2025}$) for CO_2 pilot for the local CO_2 (top) and external CO_2 (bottom) with the offsite well (PSTY01) and the onsite well (PSTY02)

5.1.4.2 *ABEX*

As assumed by Bourgeois et al (2022), the abandonment costs which will take place after the pilot operation and monitoring periods (Figure 5.2) will be assumed to vary between 10%-30% CAPEX as shown in Table 5.13

Scenario	offsite			onsite		
	P10	P50	P90	P10	P50	P90
Local CO_2	6.51	10.36	14.83	6.86	9.97	14.26
External CO_2	2.93	4.35	5.98	2.81	4.11	5.61

Table 5.13 Distribution of the ABEX (M€$_{2025}$) for the various scenarios

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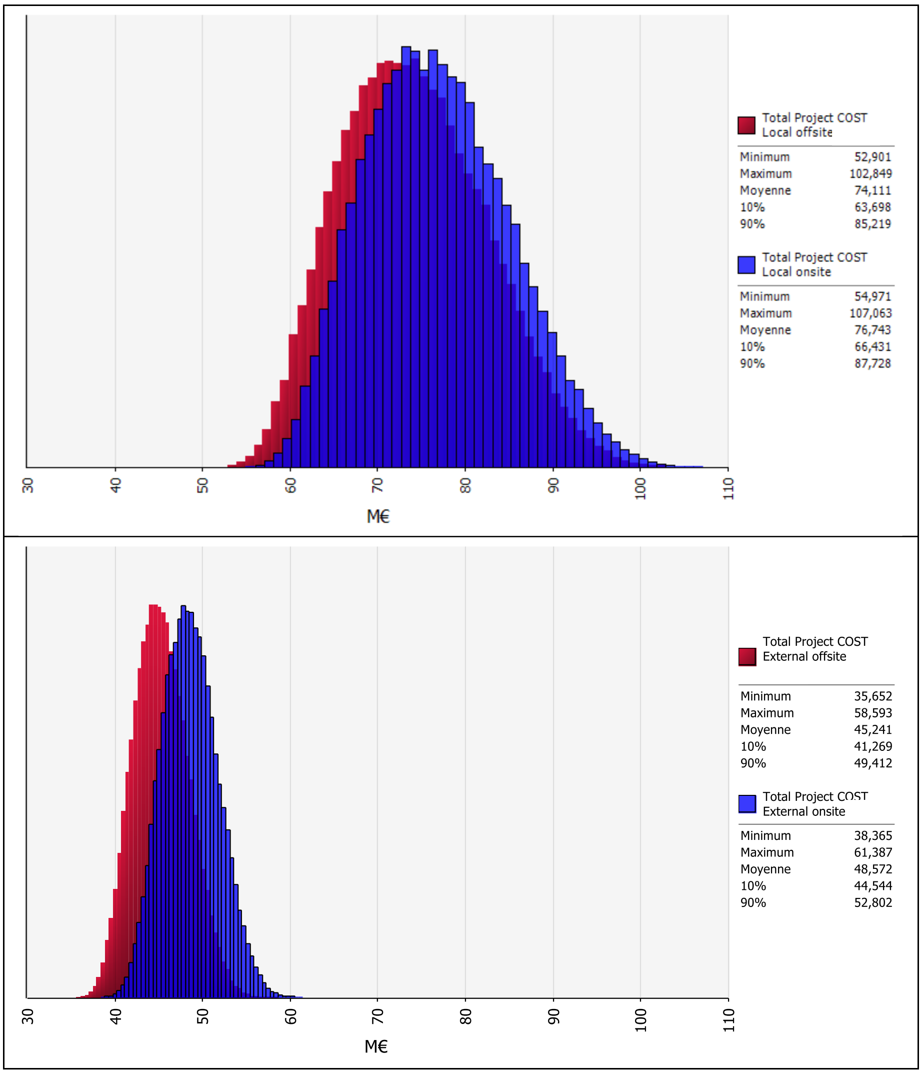

Figure 5.9 Distribution of the CO_2 pilot project cost (CAPEX+OPEX+ABEX) (M€$_{2025}$) for CO_2 pilot for the local CO_2 (top) and external CO_2 (bottom) with the offsite well and the onsite well

5.1.4.3 *OPEX*

The cost of the human resources, which are required to operate, interpret, oversee both from management and QHSE perspective, communicate with the administration and stakeholders, are not included in the current OPEX as assumed to be internal costs to the pilot operating company.

The OPEX for the external CO_2 scenario include the purchase cost of the 100kt planned in the pilot as defined in section 4 which explains the OPEX difference between local and external CO scenarios. The main cost driver between offsite and onsite scenarios is related to the well logging costs.

Scenario	offsite			onsite		
	P10	P50	P90	P10	P50	P90
Local CO_2	3.97	4.94	6.08	4.64	5.82	7.26
External CO_2	9.53	10.97	12.50	10.22	11.83	13.66

Table 5.14 Distribution of the OPEX (M€$_{2025}$) for the various scenarios

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5.1.4.4 *CO_2 pilot project*

The previous CAPEX, OPEX, ABEX distributions are added together to estimate the pilot project CAPEX as summarized in Table 5.15 and illustrated in Figure 5.9

Scenario	offsite			onsite		
	P10	P50	P90	P10	P50	P90
Local CO_2	63.70	73.66	85.22	66.43	76.28	87.73
External CO_2	41.27	45.10	49.41	44.54	48.45	52.80

Table 5.15 Distribution of the CO_2 pilot project cost (CAPEX+OPEX+ABEX) (M€$_{2025}$) for the various scenarios

5.2 Lusitanian Basin (Portugal)

5.2.1 Description of the scenario

A dedicated CO_2 injection well is planned in the offshore of the Lusitanian Basin, approximately 22 km from the coast of Figueira da Foz (Figure 5.10). The selection of the injection site in a deep saline aquifer located approximately 800 to 1000 m deep was based on an exhaustive geological characterization using existing 2D and 3D seismic datasets, data from 13 wells, outcrop data from onshore analogues, aeromagnetic data and results from a passive seismic survey. The study has also integrated an important evaluation of the CO_2 plume dispersion within the geological complex, based on advanced 3D static and dynamic models.

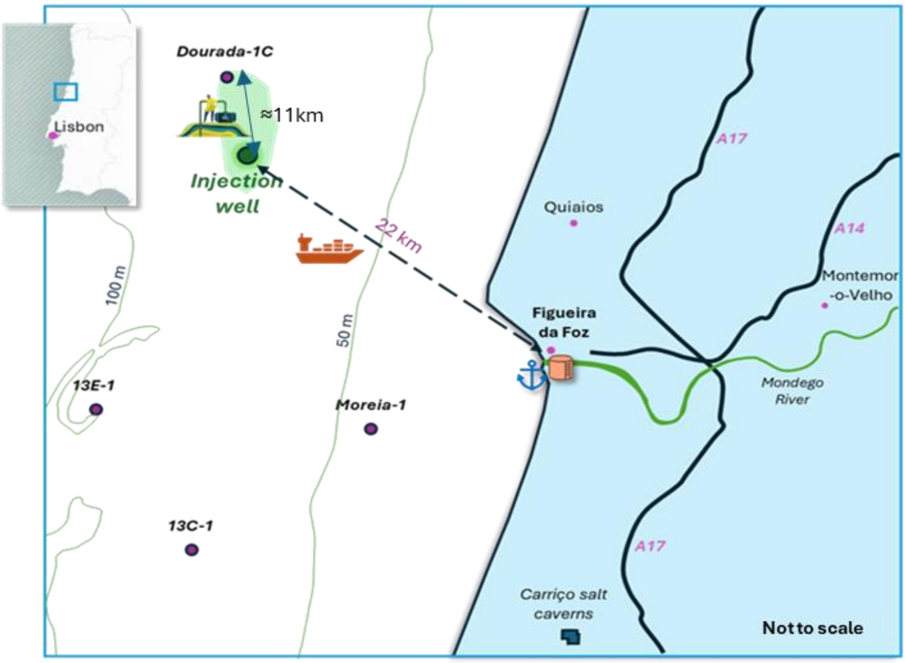

Figure 5.10: Location of the CO_2 injection well (distance not to scale)

The primary objective of the pilot phase is to evaluate the behaviour of the geological unit identified as the storage reservoir, as well as to assess the sealing effectiveness of the overlying geological formations. To reach this aim, it is planned to acquire a comprehensive logging set and conduct an advanced testing program. The pilot phase will enable the development and validation of protocols for *in situ* measurement, monitoring, and verification (MMV).

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The main source of CO_2 for pilot scale are the considered emitters interested in deploying small-scale CO_2 capture facilities, notably the cement plant located in Souselas. Flexible transport solutions were evaluated, including direct offshore injection from a ship, in order to avoid the deployment of permanent offshore pipelines or platforms. The system design aims to supply the CO_2 required for an injection pilot to validate the reservoir and injection (Figure 5.11).

The mass of CO_2 to be injected will be at maximum 100 kt of CO_2, for the purpose of the pilot design and costs evaluation, 99 kt of CO_2 were considered for a period of transport and injection that will last at most 15 months. The economic evaluation of commercial-scale deployment is not presented, as it would necessitate considering multiple CO_2 sources and additional injection wells specific to the commercial development scenario.

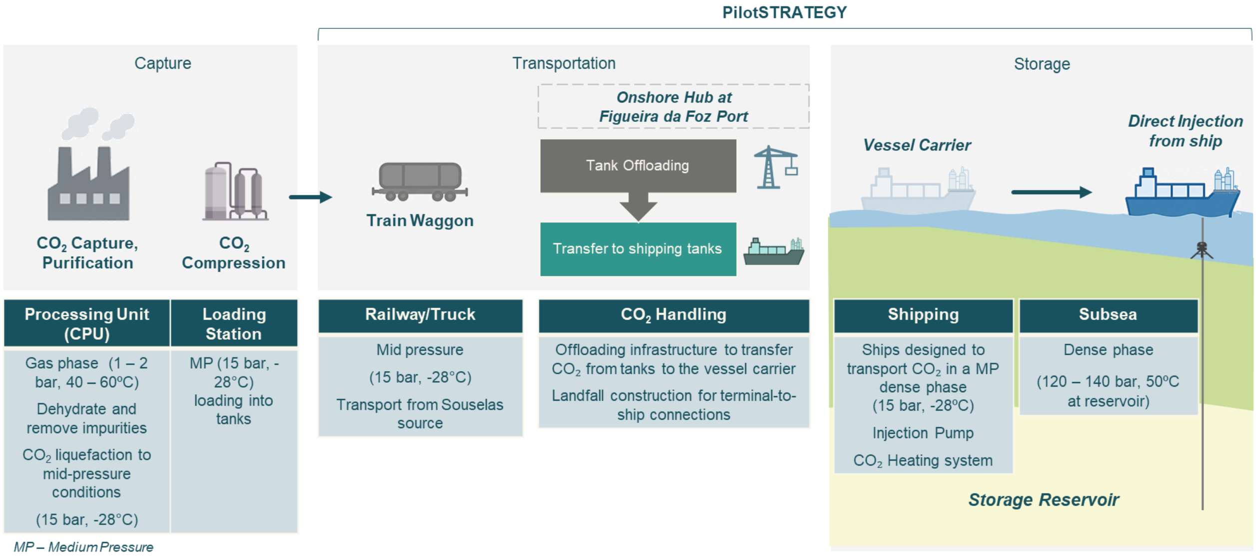

Figure 5.11: Pilot Phase description – cost structure in this report only refers to the transportation and storage phases. CO_2 pressure and temperature conditioning is indicative and may change according to operational conditions.

Geological setting

The main storage potential is identified in the Lower Cretaceous, denominated Torres Vedras Group, locally designated Figueira da Foz Formation. This formation is mainly composed by sandstones, deposited in a fluvial environment with interbedded sealing clays, that have been observed and described in some of the wells in the region. The caprock is composed by a thick sealing layer on the top of the reservoir in the upper cretaceous, which combines in the topmost part mainly limestone deposited in a marine carbonate platform and marls and clays at the base. This is a strong seismic reflector, easily identified (Figure 5.12).

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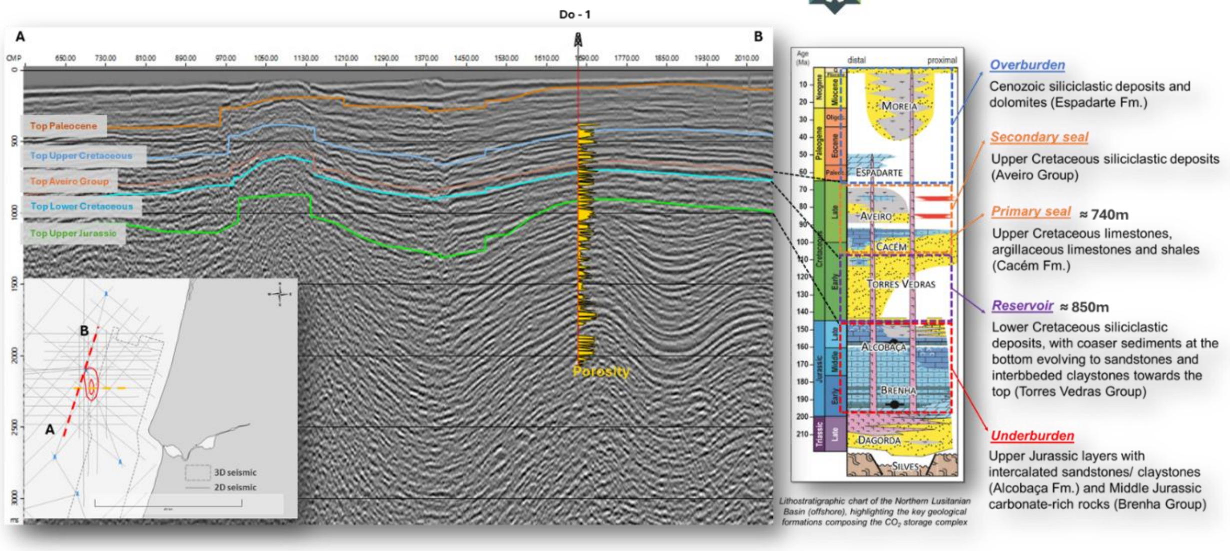

Figure 5.12: Legacy 2D seismic line and stratigraphic correlation

5.2.1.1 CO_2 transport and direct injection from ship

For the initial transport phase, CO_2 is assumed to be transported by rail from the capture facilities to the port of Figueira da Foz, followed by shipment from the port to the offshore injection site. CO_2 volumes and transport conditions will be aligned among the rail operator, port facilities, and shipping system to enable continuous transfer without intermediate storage or significant reconditioning. This approach also allows for direct injection from the ship.

Design strategy and logistic aspects

The pilot transport and injection system was designed to minimize the deployment of permanent or difficult-to-relocate infrastructure. On this basis, fixed installations such as pipelines, offshore platforms, and port facilities for intermediate storage or dedicated loading and unloading systems were deliberately avoided through the adoption of an intermodal transport solution.

Figure 5.13 illustrates the main steps of the transportation stage. (1) CO_2 transport is based on cryogenic containers loaded at the liquefaction facility located at the Souselas cement plant; (2) the containers are then transported approximately 55 km by rail to the port of Figueira da Foz, (3) where they are loaded onto a vessel that sails approximately 22 km to the offshore injection site, (4) CO_2 injection is performed directly from the vessel, eliminating the need for an offshore platform. With the exception of the liquefaction facility co-located with the capture plant, all components of the transport and injection chain are modular and can be rented, redeployed, or repurposed, supporting flexibility and cost efficiency during the pilot phase.

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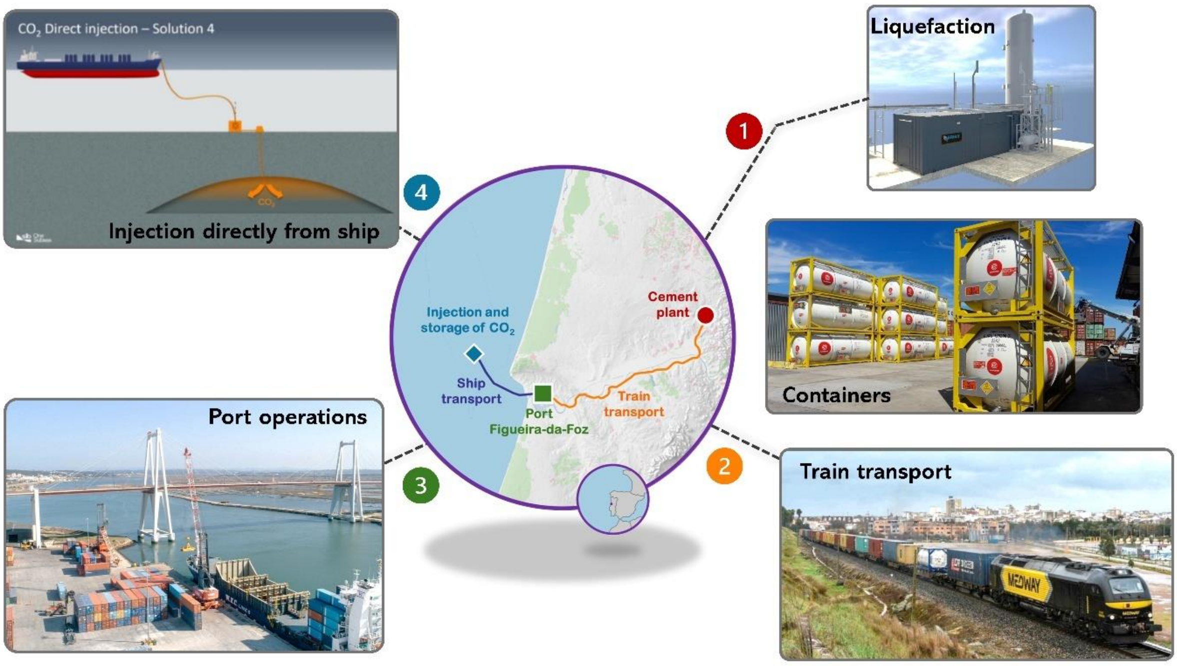

Figure 5.13: Operational sequence

Under the assumed operating conditions, approximately 650 t of CO_2 would be transported and injected per day within a 24-hour cycle, resulting in a total of 152 operating days (or round trips) to inject the full target CO_2 volume. Under idealized sequential operation, this would correspond to a total duration of approximately five months (Figure 10.14). However, continuous daily operation is not considered realistic. Assuming a five-day operational week, the required duration would increase to approximately 7.5 months. In addition, operational disruptions and non-productive periods are expected, and it is unrealistic to assume uninterrupted operation over 152 consecutive cycles. To account for these constraints, an overall system availability of 50% was assumed. Under this assumption, the maximum expected duration of the pilot injection phase increases to approximately 15 months. This duration was adopted as the basis for estimating time-dependent costs.

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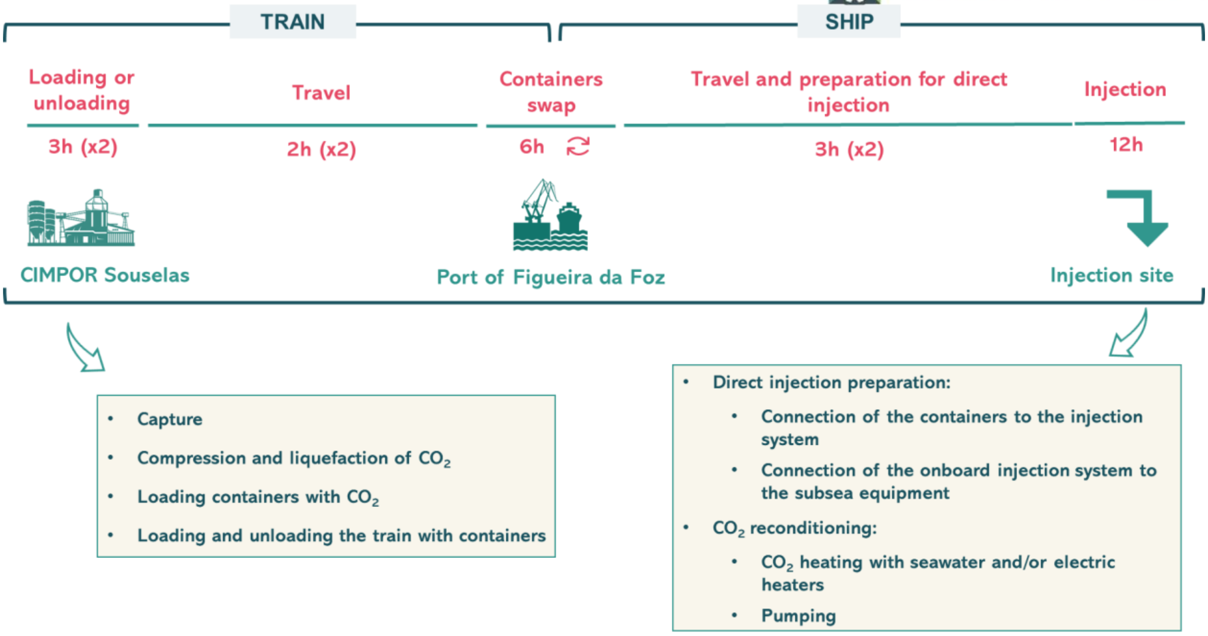

Figure 10.14: Ideal day of operations, from capture to injection

5.2.2 Drilling and completion

The CO_2 exploration and injection well was designed in accordance with current industry best practices to ensure cost efficiency, operational safety, and environmental protection. Nevertheless, the well is conceptualized based on the limited available information regarding subsurface conditions. The planned total depth (TD) of the well is 1,400 m, providing adequate vertical separation and integrity margins for two injection intervals located at approximately 1,025 m and 1,155 m depth (Figure 5.15).

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. The BOP is a high-pressure safety system installed above the wellhead to maintain well control during drilling and completion operations. Its primary functions include isolating the wellbore in the event of abnormal pressure conditions and preventing the uncontrolled release of formation fluids, thereby protecting personnel, equipment, and the environment.

Ensuring the chemical compatibility of all well components is critical to maintaining long-term integrity. Materials must be resistant to corrosion resulting from carbonic acid formed through CO_2–water interactions, as well as to embrittlement associated with impurities such as hydrogen sulfide (H_2S) and hydrogen. In scenarios where injection pressures exceed the formation fracture closure pressure, the production packer must be installed at an adequate depth to prevent casing deformation, caprock fracturing, or unintended fluid migration into overlying formations under maximum injection conditions. Continuous monitoring of annular pressures, injection rates, and temperature profiles is essential throughout operations to enable early detection of leaks, mechanical failures, or other operational anomalies.

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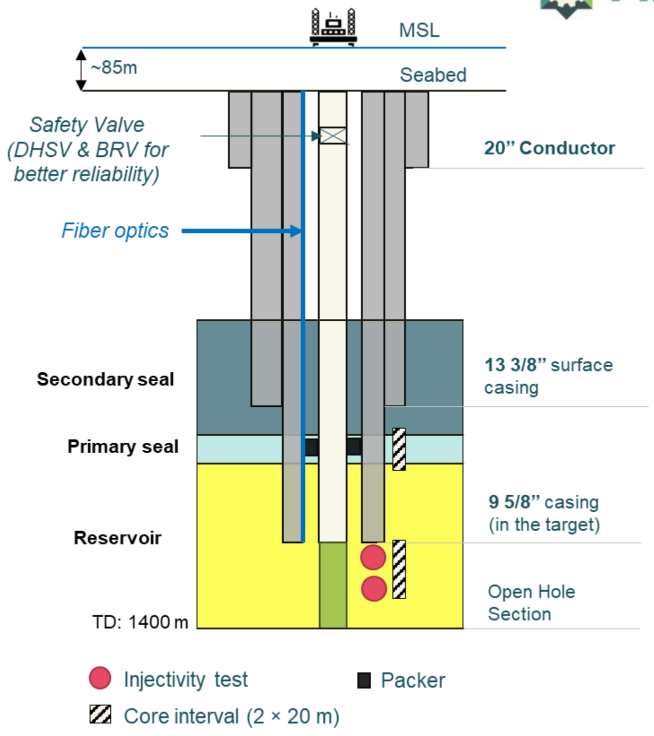

Figure 5.15: Well design

During completion of the injection well, the wellbore is filled with a completion fluid, typically a clean, particle-free brine, to prevent damage to the formation and avoid blockage of perforations. The fluid is selected to be chemically compatible with the reservoir rock and fluids and to provide the required hydrostatic pressure within the wellbore. A high-density brine is commonly used to maintain an overbalanced condition relative to formation pore pressure, thereby ensuring wellbore stability and effective control of formation fluids throughout completion operations.

For offshore drilling of CO_2 injection wells in shallow to medium water depths (up to approximately 150 m), jack-up rigs are commonly employed, as demonstrated by projects such as the Greensand CCS project in Denmark. These self-elevating units provide a stable working platform for accurate drilling and well completion operations and are generally more cost-effective than fixed offshore platforms in shallow-water CCS applications. Jack-up rigs consist of a buoyant hull fitted with movable legs that can be lowered to the seabed, allowing the hull to be elevated above sea level during operations.

5.2.3 Seismic data acquisition

It is planned to acquire a 3D reflection seismic survey to complement the data provided by the existing 2D and 3D seismics, since the latter does not cover the entire storage site, and to provide the baseline for monitoring (Figure 5.16).

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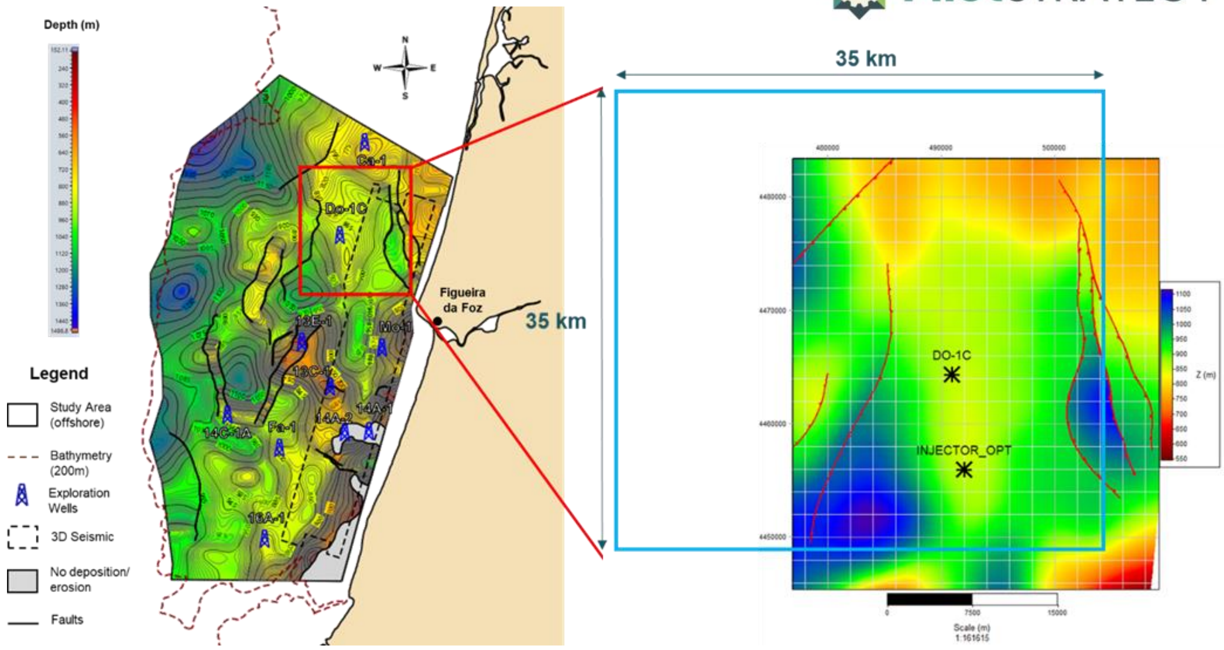

Figure 5.16: Location of the 3D seismic survey, in the offshore of the Lusitanian Basin. Full fold area is identified in blue rectangle

The proposed 3D seismic acquisition campaign covers a full-fold area of approximately 1,225km² (35×35km), encompassing the planned CO_2 injection site and its surrounding region. The survey area was deliberately extended beyond the immediate prospect to include adjacent zones currently lacking 3D seismic coverage, ensuring continuity and completeness of geophysical information for characterization of the storage complex, with particular emphasis on the reservoir and caprock.

The westward and northward extensions of the survey area are critical for improved delineation of fault continuity, connectivity, and transmissibility, which are key parameters for assessing potential induced seismicity. The expanded coverage also supports long-term monitoring of CO_2 plume migration and pressure propagation. In particular, it enables adequate spatial coverage of the pressure front over the anticipated 30-year injection period, facilitating time-lapse (4D) seismic analysis of pressure and CO_2 saturation changes based on repeated 3D surveys. The broader area further supports optimization of injection and monitoring strategies, including the evaluation of potential locations for additional injection wells.

The water depth across the survey area is approximately 85 m, corresponding to shallow-water conditions. The primary imaging targets are located between approximately 800 and 1,400 m TVDSS and include both the storage reservoir and the overlying sealing formations.

The objectives of the seismic survey are to provide robust data to:

- Support CO_2 injection well design by confirming site location, depth prognosis, and identifying potential drilling hazards.
- Characterize the structural framework, stratigraphy, and fluid properties of the storage complex (reservoir and caprock), enabling advanced structural and stratigraphic interpretation and quantitative seismic analysis (e.g. seismic inversion).

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- Improve regional characterization around the injection site, including overlap with the existing 3D Cabo Mondego seismic survey to the east, and to replace reliance on legacy 2D seismic data that currently constrain more than half of the prospect area.
- Assess potential induced seismicity risks through detailed characterization of fault systems, particularly in the structurally complex western sector of the site and establish a baseline for long-term seismicity monitoring.
- Establish a pre-injection (baseline) dataset for long-term monitoring of CO_2 plume evolution, pressure propagation, and pressure front development using 4D seismic time-lapse analysis.
- Support optimization of injection and monitoring strategies, including the assessment of additional injection well locations for future commercial-scale deployment.
- Enable multi-component seismic recording to enhance subsurface characterization.

An offshore Extended High Resolution (XHR) mini-streamer 3D seismic acquisition campaign is recommended, with operations planned to commence in 2027, subject to geophysical and logistical constraints. This acquisition approach is well suited to detailed subsurface imaging for both geological characterization and long-term CO_2 storage monitoring.

A schematic illustration of a mini-streamer seismic survey is shown in Figure 5.17. During acquisition, a seismic vessel tows multiple short streamers equipped with hydrophones below the sea surface. Acoustic energy is generated using compressed air guns, and reflected seismic signals from subsurface geological interfaces are recorded by the hydrophones. Processing of these data yields a high-resolution three-dimensional image of the subsurface.

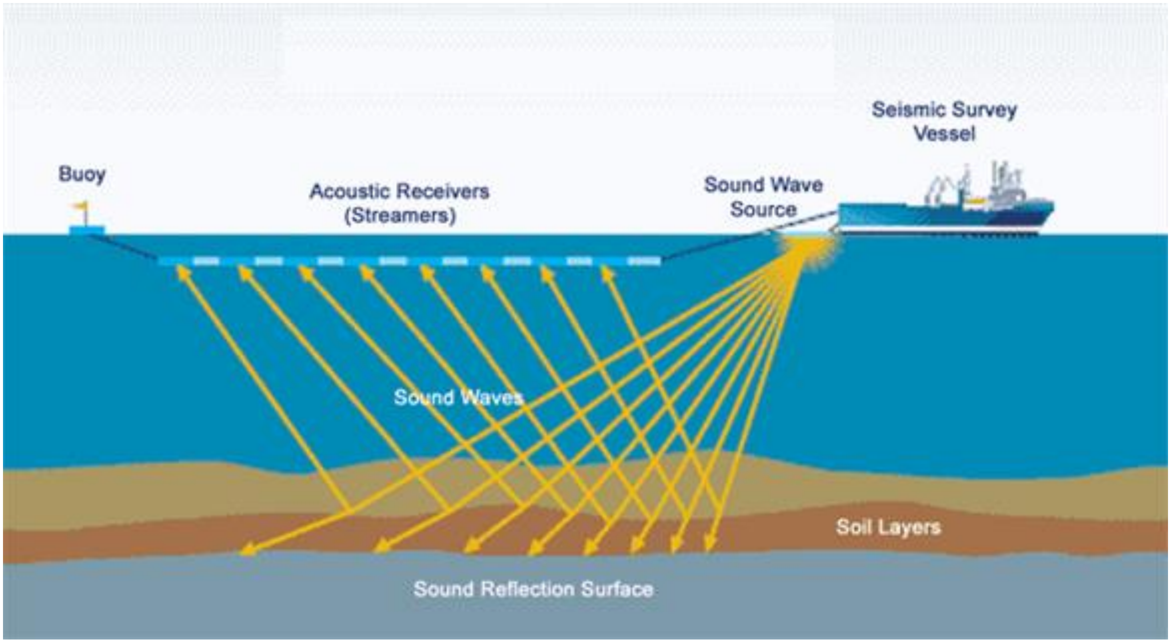

Figure 5.17: Illustration of seismic surveying with streamers (https://fishsafe.org/en/offshore-structures/seismic-surveys/)

5.2.4 MMV

The MMV framework is designed to ensure permanent containment and conformance of injected CO_2 within the designated storage complex, protection of the marine environment and human health,

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compliance with Directive 2009/31/EC, Decree-Law 60/2012 and relevant OSPAR guidelines, and accurate quantification of stored CO_2 in accordance with international reporting standards (Veloso et al. 2024).

The main objectives of the MMV plan are to:

- Verify that injected CO_2 behaves in accordance with model predictions
- Detect any unintended migration or leakage of CO_2
- Assess potential significant adverse effects on the environment or human health
- Evaluate the effectiveness of corrective measures, if required

Monitoring architecture is vertically integrated and structured according to the components of the storage complex: subsurface reservoir and overburden, injection well, seabed interface, and overlying water column (Figure 5.18). Baseline data acquisition is implemented across all monitoring domains prior to injection in order to define natural background conditions and establish reference envelopes for anomaly detection.

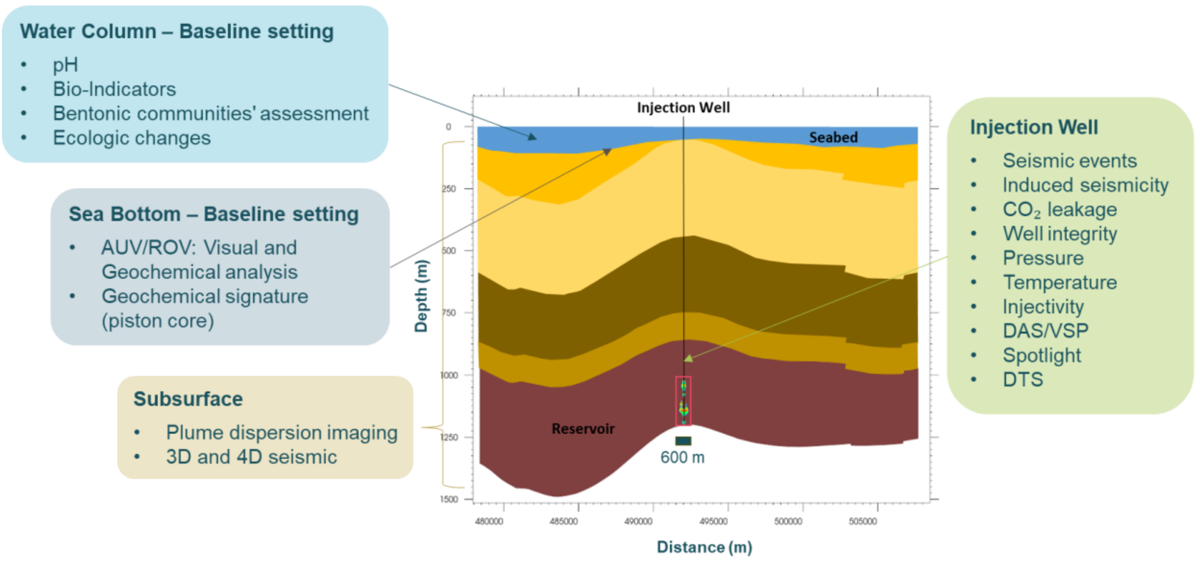

Figure 5.18: Schematic summary of MMV framework considered for the Lusitanian Basin project

Monitoring domains extend from the deep subsurface reservoir and overburden, through the injection well system, to the seabed interface and overlying water column. During the pilot phase (2027–2033; <100 kt CO_2), monitoring is implemented in a proportionate manner, aligned with the limited injection scale while remaining technically scalable to future commercial deployment.

Subsurface monitoring combines high-resolution 3D baseline seismic acquisition using XHR mini-streamer technology with time-lapse (4D) repeat surveys to track plume migration and pressure evolution. This is complemented by continuous well-based measurements, including pressure monitoring and Distributed Acoustic Sensing (DAS) installed along the injection well, enabling near-wellbore acoustic and strain surveillance. Well monitoring also includes downhole pressure and temperature sensors, seafloor monitoring instruments (e.g. acoustic leak detectors or chemical sensors), and periodic well integrity logs (through-tubing measurements). Additional lower-cost, multi-point measurement systems (e.g. SpotLight-type technologies) may be deployed to enhance

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spatial coverage through interpolation. Together, these tools provide a multi-scale assessment of plume behaviour, geomechanical response and potential deviation from predictive reservoir models.

Seafloor monitoring integrates Multibeam Echosounder (MBES) bathymetric mapping, sedimentological and porewater geochemical baseline characterisation, and habitat-stratified biological surveys implemented under a BACI/Beyond-BACI framework. Repeat MBES surveys allow quantitative detection of morphological change through digital terrain model differencing, while geochemical parameters define baseline carbonate system conditions against which potential perturbations can be assessed. Targeted seabed investigations may be supported by AUV-based systems equipped with sediment corers and samplers.

Water column monitoring follows a T-based structure (Before – Occurrence – After), comprising seasonal CTD profiling and carbonate system measurements to define hydrographic and biogeochemical baseline. Given the limited injection scale during the pilot phase, water column monitoring functions primarily as a confirmatory safeguard layer, with intensified surveys implemented only if triggered by subsurface or seabed indicators.

Following cessation of injection, monitoring intensity is progressively reduced during the post-injection period, focusing on confirmation of pressure stabilisation, plume distribution and immobilisation, and the absence of measurable perturbations at the seabed and water column interfaces. Overall, the MMV architecture is designed to validate predictive models, detect deviations from defined baseline envelopes, and ensure permanent containment while maintaining proportionality and regulatory compliance throughout the project lifecycle.

For the commercial phase, monitoring frequency and spatial coverage will be scaled accordingly to reflect increased injection volumes and regulatory requirements. Further technical details regarding monitoring technologies, spatial design, frequency, thresholds and escalation protocols are provided in Deliverable D4.6.

5.2.5 Description of the economic assumptions

The economic assessment focuses on the pilot stage, as it represents the most realistic and near-term investment framework. Pilot activities are assumed to be conducted within the regulatory scope of a scientific research project, enabling a more streamlined permitting process for seismic acquisition and well drilling. Provision is made for a potential transition to a commercial phase, subject to a future re-evaluation of costs, regulatory requirements, and permitting conditions.

The overall project timeline is presented in Figure 5.19 and indicates a pilot duration of approximately seven years, which forms the basis of this economic evaluation. The key project milestones are:

- 2027–2028: 3D seismic acquisition and processing
- 2030: Drilling and well completion
- 2031–2032: CO_2 injection phase (approximately 15 months; ~99 kt CO_2)
- 2033: Completion of the pilot phase

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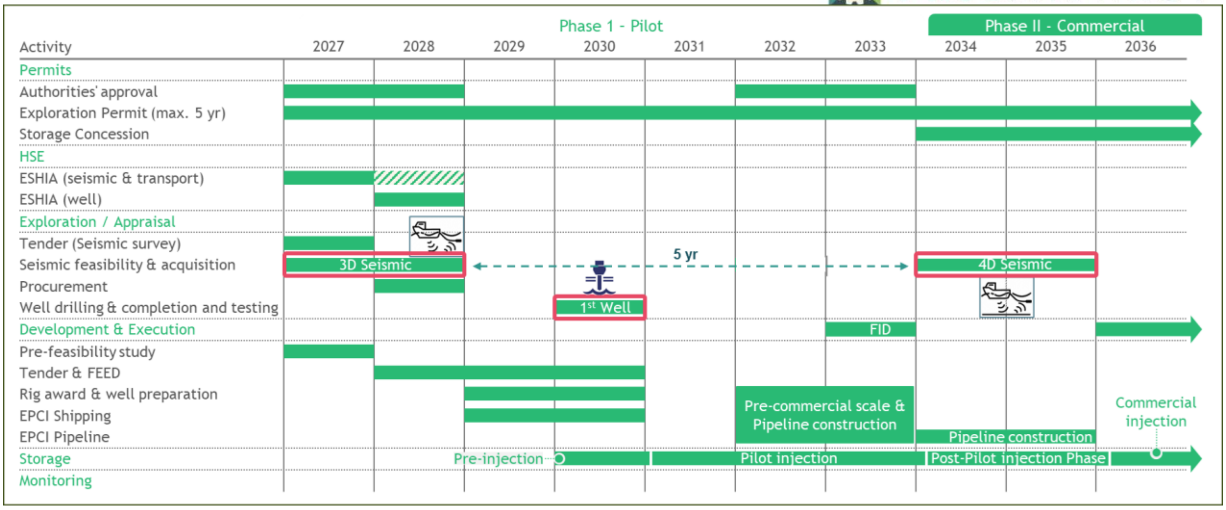

Figure 5.19: Project timeline, with the main operations highlighted (seismic acquisition and well drilling)

5.2.6 CO_2 Transportation and Injection cost

The transportation and injection costs refer to the costs from CO_2 Conditioning, Train and Port Operations and Shipping and Injection, as described in 5.17.

Table 5.17: CO_2 Transportation and Injection activities considered for cost estimation

CO_2 Conditioning	Train and Port Operations	Shipping and Injection
Compression and liquefaction	Railway transport	Ship rent
Loading containers with CO_2	Containers rent	Port fees + Fuel
	Containers transfer in port	CO_2 reconditioning for injection

Costs were obtained with different methods depending on the component being assessed. Most of the operational costs were obtained by consultation, either directly with the service providers or with knowledgeable companies with experience in the specific operation. The remaining costs were calculated from literature models using the CO_2 mass, pressure and temperature conditions. Depending on the type of operation or equipment, costs were assessed either by number of roundtrips (152), number of days (450), or CO_2 mass (99 kt).

CO_2 conditioning

Conditioning costs were split in compression, liquefaction and loading of the CO_2 into the containers. These costs were calculated based on literature models for 99 kt of CO_2. The initial conditions of the CO_2 were considered as 1 bar and 35°C and the output conditions of the liquefied CO_2 15 bar and -29°C (Table 16.18).

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Table 16.18: CO_2 Conditioning cost breakdown

Equipment/Operation	Cost	Assumptions	Total cost	Source
Compression and liquefaction	Capex: 3.4 €M Opex: 0.8 €M	99 ktCO_2	4.2 €M	GCCSI (2005)
Containers loading and unloading	Capex:0.3 €M Opex:0.1 €M	99 ktCO_2	0.4 €M	Element Energy (2018)
		Total	4.6 €M	

Train transport and port operations

Train transport and port operations costs were obtained by consultation with the relevant operators for each process. Train transport cost was supplied on a roundtrip basis by the train operator MEDWAY, that also provides the cryogenic containers to be rented daily. Port operations costs, which involve the loading and unloading of the containers from both train and ship, were provided by Yilport, that operates in the Figueira da Foz port, these costs were assessed on a "per movement" cost (Table 5.19).

Table 5.19: Train transport and port operation costs breakdown

Equipment/Operation	Cost	Assumptions	Total cost	Source
Cryogenic containers	20€ per day per container	90 containers rented for 450 days	0.8 €M	Train operator, Medway[11]
Train transport	13 500€ per trip	152 trips	2.1 €M	Train operator, Medway[11]
Container loading or unloading from train	25 € per movement, per container	30 containers loaded and unloaded from train per trip	0.2 €M	Port operator, Yilport[12]
Container loading or unloading from ship	135 € per movement, per container	30 containers loaded and unloaded from ship per trip	1.2 €M	Port operator, Yilport[12]
		Total	*4.3 €M*	

[11] https://www.medway-iberia.com/pt
[12] https://yilport.com/pt/

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Shipping and direct injection operations

Shipping and direct injection operations were divided in ship rent, port fees, and fuel costs. Marine vessel operator HAYS SHIPS provided a description of needs and costs related with the ship. The remaining costs were calculated, port fees by considering 152 entries and exits; transport fuel for 50 km roundtrip distance; and CO_2 heating and pumping for 99 kt of CO_2. Reconditioning OPEX includes fuel costs to source the needed energy (Table 5.20).

Table 5.20: Shipping and direct injection operations costs breakdown

Equipment/Operation	Cost	Assumptions	Total cost	Source
Ship rent	20 000 € per day	450 days	9.0 €M	Hays ships consulting[13]
Port fees and transport fuel		152 trips and 50 km roundtrip	2.2 €M	Element Energy (2018)
CO_2 reconditioning	Capex:3.0 €M Opex:0.2 €M	99 ktCO_2	3.2 €M	CEMCAP (2018)
		Total	*14.4 €M*	

5.2.7 Subsea costs

The parallelism between CO_2 injection equipment with technologies used in the oil and gas industry imply that it will be reasonable to assume a setback free implementation on the short term. The direct injection system components (Table 5.21) were grounded on high-level bulk cost assessment provided by NEMO maritime[14] and OneSubsea[15] and adjusted to account for the local conditions at the pilot site (e.g. water depth). For this cost analysis, 25 €M CAPEX were considered to cover the components for the connection between the ship and the wellhead, including riser hose, riser bed and Xtree.

OPEX cover the day-to-day costs of keeping the operation running, including personnel, logistics, maintenance and subsea equipment maintenance. As usual practice in at this level of analysis, OPEX was assumed as 5% of the subsea CAPEX costs.

Table 5.21: Subsea components for connection between ship and wellhead

Subsea
Riser float, Riser hose with umbilical connection, Riser bed with swivel
Jumper
Xtree, Xtree control module

[13] https://haysships.com/
[14] https://www.nemomaritime.com/
[15] https://www.onesubsea.slb.com/

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5.2.8 Drilling and Completion cost

The assessment of the drilling and completion cost associated with the CO_2 injection well are based on expert feedback in alignment with current market conditions. The cost reflects the folded objective of the well, i.e., exploratory character and injection purposes. The Drilling and Completion (D&C) costs activities considered for cost estimation are presented in Table 5.22.

Table 5.22: Drilling and completion costs activities considered for cost estimation

Drilling & Completion
Mobilization / Demobilization
Drilling operations
Data Acquisition
Completion

Ensuring well integrity for CO_2 injection well demands a robust design and strict compliance with containment principles, given the challenging conditions created by CO_2 as described in section 5.2.2. The materials used for a CO_2 injection well completion must withstand a harsh CO_2 environment and are more expensive and typically have longer lead times than the standard materials.

It is considered extensive data acquisition and advanced well testing to enable characterization and evaluation of the reservoir and overlying sealing formations (i.e., core data, advanced logging, injectivity testing, pressure and temperature measurements) in order to provide comprehensive subsurface data to prove the site is suitable and safe for CO_2 injection. Thus, the well cost will include acquisition of the necessary amount of data. The well will be eventually P&A according to industry best practices and standards.

The drilling operations represent approximately one third of the total D&C costs, being the other most significant costs related with data acquisition, completion and P&A. Due to the early stage of the project, the OPEX has been assigned as a notional representing 5% of the CAPEX, considering mainly the well maintenance, well testing, logistics and support. Well maintenance for CO_2 injection focuses heavily on maintaining wellbore integrity against corrosion and pressure changes, involving routine inspections, well intervention (slickline/coiled tubing) for monitoring and minor fixes, well workovers for major repairs, and advanced pressure management systems, alongside specialized training due to CO_2's unique behaviour (e.g., acidification, phase changes). Key activities include Xmas tree maintenance, integrity logging, cement repairs (squeeze cementing), and rigorous monitoring of pressures, temperatures, and fluid chemistry.

5.2.9 Seismic costs

The seismic cost estimate is based on the acquisition and processing of a dedicated offshore 3D seismic survey to support detailed characterization and long-term monitoring of the CO_2 storage complex in the Lusitanian Basin. The survey covers a full-fold area in shallow-water conditions, encompassing the

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planned injection site and its surroundings, and extending beyond the immediate prospect to ensure adequate regional coverage.

Table5.23: Seismic activities considered for cost estimation

Seismic
Acquisition (includes mob/demob)
Processing

The acquisition scope includes mobilization/demobilization, seismic vessel charter, source and streamer deployment, and data acquisition. An XHR mini-streamer 3D configuration is assumed, enabling high-resolution imaging of the reservoir and caprock, fault characterization, and the establishment of a robust baseline for future 4D seismic monitoring of CO_2 plume migration and pressure evolution.

Processing costs include standard and advanced workflows required to deliver an interpretation-ready 3D seismic volume, supporting structural interpretation, stratigraphic analysis, and quantitative seismic applications. Cost estimates are based on expert feedback and current market benchmarks, consistent with an AACE Class IV cost estimate. Seismic costs are classified entirely as CAPEX, with no associated OPEX considered.

The most likely seismic CAPEX is estimated at €13.8 million, comprising approximately €12.5 million for acquisition and €2.3 million for processing. For the probabilistic assessment, a -30% / +50% uncertainty range was applied, resulting in an estimated P10–P90 range of €9.7–20.7 million.

5.2.10 Other costs

MMV

MMV activities are cost-effective for monitoring, often valued in the range of hundreds of thousands of dollars for acquisition campaigns. In the current assessment, they are assumed to be residual costs considered in the contingency.

ABEX

The Abandonment Expenditure costs refer to the total costs required to decommission, shut down, and remediation at the end of the project life cycle. As the current evaluation refers only to the Pilot scale, the main costs refer to the well abandonment, i.e, plugging and abandoning (P&A) the well with cement to prevent CO_2 leaks into groundwater. The environmental remediation costs related with site clean-up and restoration of the surrounding area, are considered residual and within the contingency. As such, for probabilistic assessment purposes, three scenarios of ABEX have been considered:

- Low case: assuming that there is a subsequent commercial scale, as such the costs are zero
- Base case: considering 10% of the D&C CAPEX
- High case: considering 30% of the D&C CAPEX

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Table 5.24 summarizes the reference values of all the costs considered into the economical evaluation at the pilot scale and described previously in detail. The probabilistic economic assessment presented on section 5.2.11 considers these values as most likely.

Table 5.24: Summary table with the reference cost estimation

M€	CAPEX	OPEX	CAPEX + OPEX
CO_2 Conditioning	**3.7**	**0.9**	**4.6**
Compression and liquefaction	3.4	0.8	
Loading containers with CO_2	0.3	0.1	
Train and Port Operations		**4.3**	**4.3**
Railway transport		2.1	
Containers rent		0.8	
Containers transfer in port		1.4	
Shipping and Operations	**3.0**	**11.4**	**14.4**
Ship rent		9.0	
Port fees + Fuel		2.2	
CO_2 reconditioning for injection	3.0	0.2	
Subsea (**CONNECTION SHIP TO WELL: RISER HOSE, RISER BED AND XTREE)**	**25.0**	**1.3**	**26.3**
Drilling & Completion	**30.0**	**1.5**	**31.5**
Seismic	**13,8**		**13.8**
Acquisition (includes mob/demob)	12.5		
Processing	2.3		
Total CAPEX (m€)	**75.5**		
Total OPEX (m€)		**19.4**	
Total CAPEX+OPEX (m€)			**94.85**
Total ABEX (m€)			**3.15**
Total CAPEX+OPEX +ABEX(m€)			**98**

5.2.11 Economic assessment

A probabilistic assessment of CAPEX, OPEX, and ABEX was conducted based on an AACE International Class IV Cost Estimate Classification. This classification carries a target accuracy range of -30% to +50%. Therefore, cost profiles were modelled using PERT distributions, defined by minimum (-30%) and maximum (+50%) bounds relative to the most likely values (Tabl). Detailed distributions for CAPEX and OPEX are provided in Figure 5.20 and Figure 5.21, respectively. A summary is presented in

Table 5.25 and Table 5.26, presenting the maximum, minimum, most likely and average values of each variable. All train and port operations are classified as OPEX as they represent rental expenditures, while seismic costs are categorized entirely as CAPEX.

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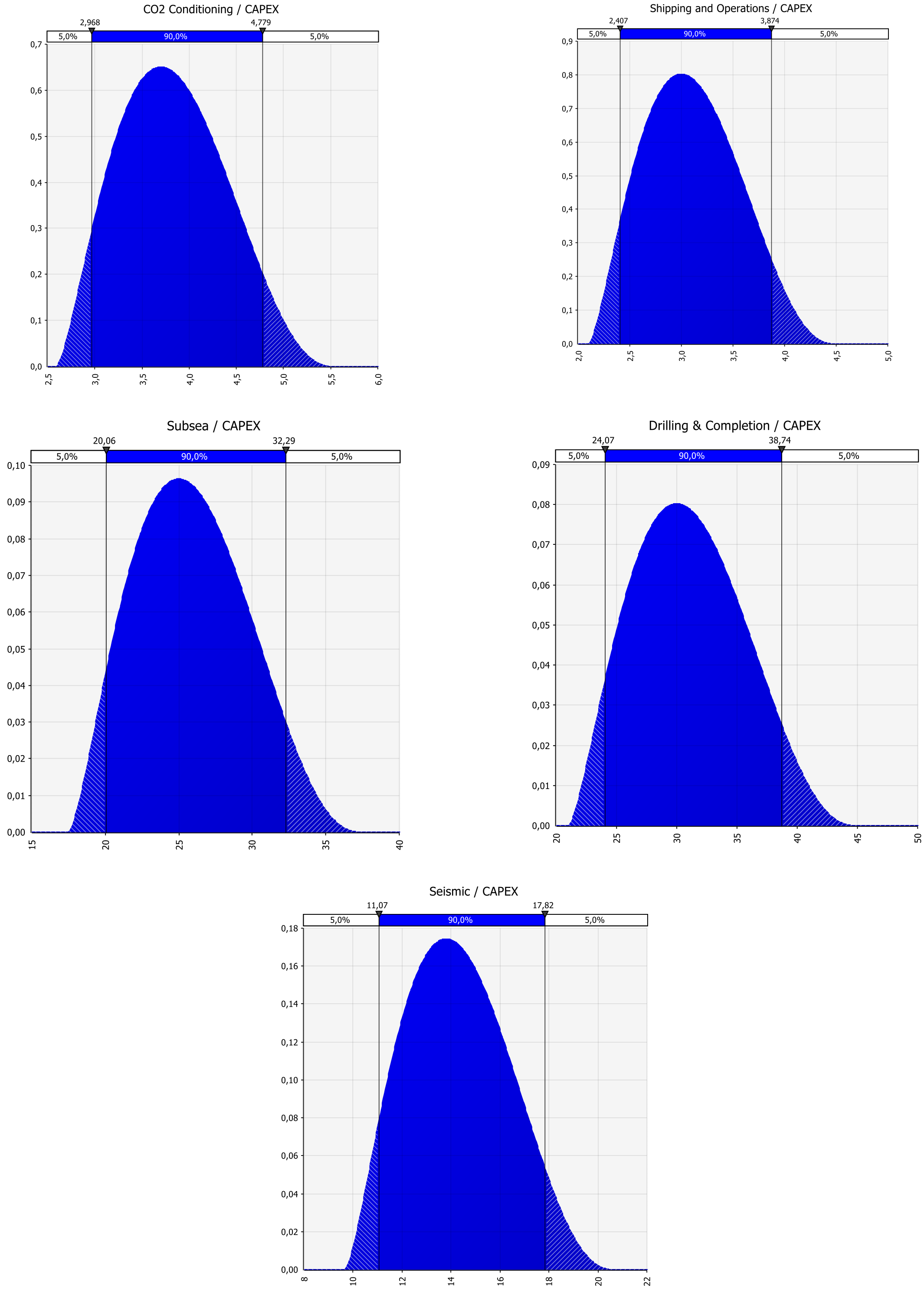

Figure 5.20: CAPEX probability distribution functions (x-axis in M€, y-axis is frequency).

Table 5.25: Summary of CAPEX

M€	CAPEX

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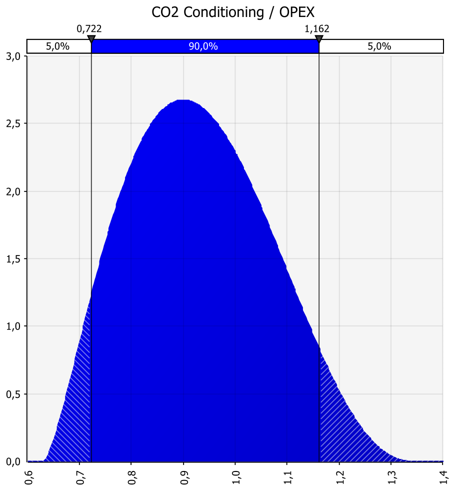
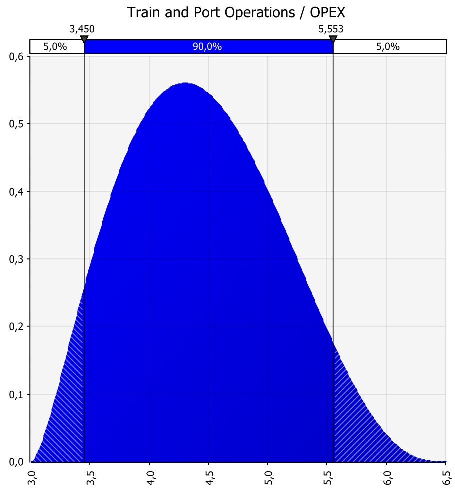
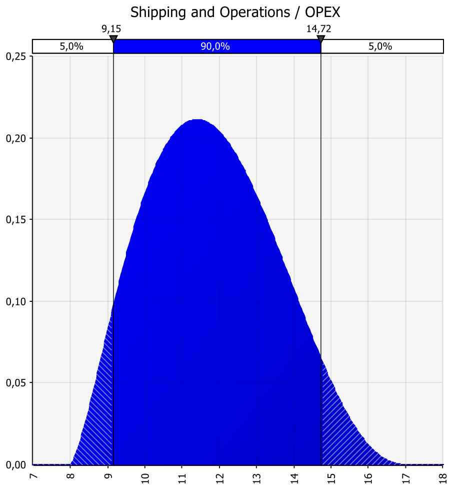
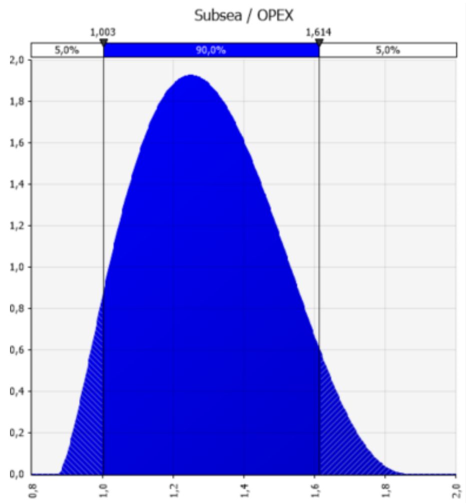
	Average	Minimum	Most Likely	Maximum
CO_2 Conditioning	3.8	2.59	3.7	5.55
Train and Port Operations	N/A			
Shipping and Operations	3.1	2.1	3	4.5
Subsea	25.8	17.5	25	37.5
Drilling & Completion	31.0	21	30	45
Seismic	14.3	9.66	13.8	20.7









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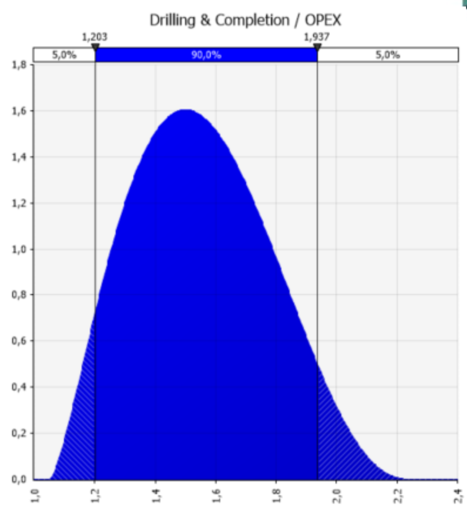

Figure 5.21: OPEX probability distribution functions (x-axis in M€, y-axis is frequency).

Table 5.26: Summary of OPEX

M€	OPEX			
	Average	Minimum	Most Likely	Maximum
CO_2 Conditioning	0.9	0.63	0.9	1.35
Train and Port Operations	4.4	3.01	4.3	6.45
Shipping and Operations	11.8	7.98	11.4	17.1
Subsea	1.3	0.875	1.25	1.875
Drilling & Completion	1.6	1.05	1.5	2.25
Seismic	N/A			

The probabilistic cost assessment was conducted using a Monte Carlo simulation methodology, for each project expenditure category. Monte Carlo simulation offers significant advantages for cost estimation by providing a more comprehensive, probabilistic view of potential project outcomes compared to traditional single-point estimates. Unlike deterministic methods, Monte Carlo simulation incorporates uncertainty and variability in input variables (represented by the distributions of each cost category). This approach generates a wide range of possible total costs and their associated probabilities. By understanding the full spectrum of potential outcomes and their probabilities, decision-makers can make more informed, data-driven decisions that align with their risk tolerance. 5000 iterations were run for each of expenditure category and the results are presented as a probability distribution of outcomes (CAPEX: Figure 5.22; OPEX: Figure 5.23, ABEX: Figure 5.24).

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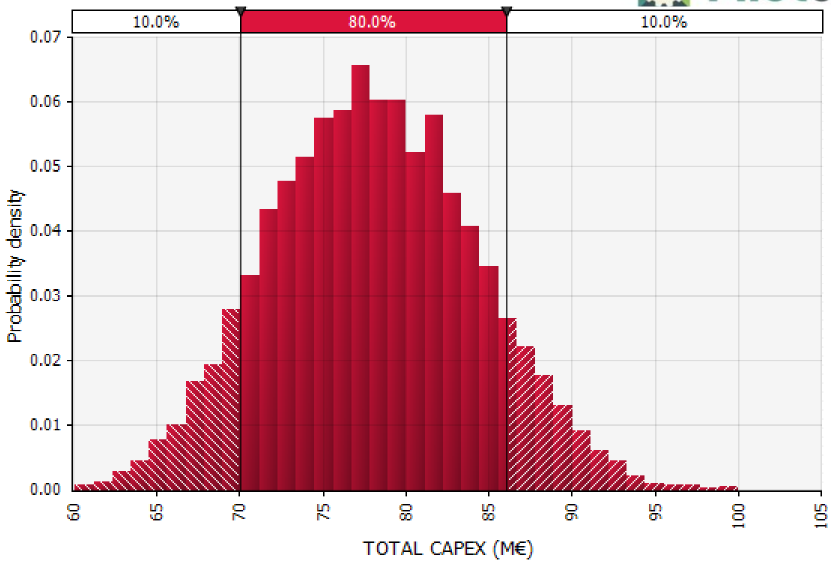
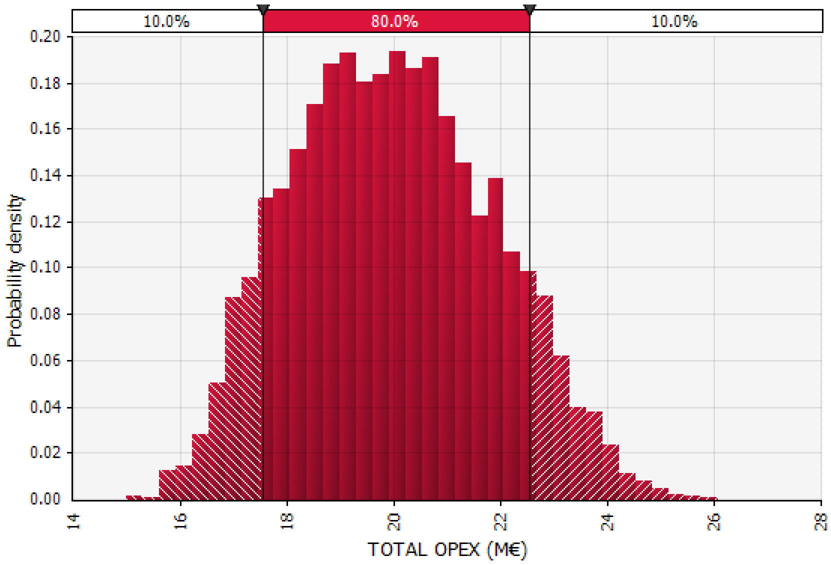


p10	70.2
p50	78.0
p90	86.3

Figure 5.22: CAPEX probability distribution function (M€)



p10	17.6
p50	19.9
p90	22.4

Figure 5.23: OPEX probability distribution function (M€)

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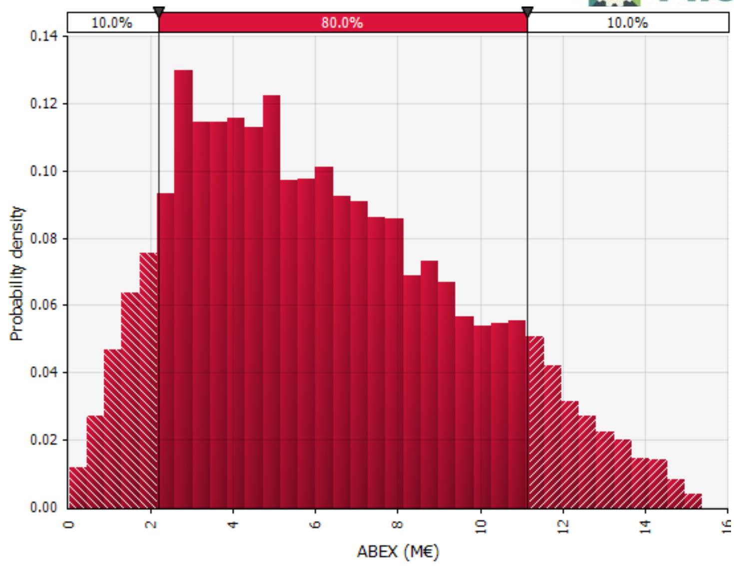

p10	2.2
p50	5.6
p90	11.3

Figure 5.24: ABEX probability distribution function (M€)

5.2.12 Synthesis

From an investment standpoint, the cost reflects the combination of CAPEX, OPEX, and ABEX components across different probability scenarios. The distribution of costs is presented in Table 5.27

Table 5.27: Cost distribution

Scenario	CAPEX (M€)	OPEX (M€)	ABEX (M€)	Total (M€)
p10	70.2	17.6	2.2	90.0
p50 (base)	78.0	19.9	5.6	103.5
p90	86.3	22.4	11.3	120.0

5.3 Ebro Basin (Spain)

5.3.1 Description of the scenarios

The CO_2 storage project in the Ebro Basin proposes the full life cycle analysis of an onshore structure including exploration phase, a 3-year injection pilot or pre-commercial phase, and a commercial development phase. Lopin site is a deep saline aquifer in Belchite area (province of Zaragoza, Spain). Ebro basin case doesn´t include capture source or analyse capture possibilities and costs. The CO_2 is assumed from a local industrial source (there are several candidate emitters in the region in a 60 km radius) and, for all of them, there are developed captured technologies to be applied. Costs, design and CO_2 quality is assumed on the standards. As well, Ebro basin case doesn´t include transport

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

Following the methodology applied in the Paris and Lusitania Basins, the Spanish team has defined a pre-commercial scenario comprising an exploration phase and a pilot phase, with a total injection of approximately 100,000 tonnes of CO_2 over three years using a single well. Subject to the success of this stage, a larger-scale commercial scenario is considered, involving one or two injection wells depending on the estimated storage capacity, ranging from 2 to 35 million tonnes of CO_2.

Figure 5.23: Pilot and commercial development scheme.

For both the pre-commercial and commercial scenarios, the availability of CO_2 from a nearby industrial source is assumed. As a result, CO_2 capture and transport costs are excluded from this analysis, and it is assumed that the delivered CO_2 meets the required quality specifications. This focused scope allows a realistic assessment of the technical and economic feasibility of CO_2 storage at the Lopín site by comparing minimum and expanded development options. The overarching objective is to evaluate whether the Ebro Basin site can advance towards a technically and commercially viable carbon capture and storage (CCS) solution within the current Spanish and European regulatory framework, using both deterministic and probabilistic evaluations to support decision-making

Due to the low density of data from the area, the uncertainties around static and dynamic modelling are key for the evaluation of the potential, and the impact of those uncertainties must be also evaluated. In this case, techno-economically assessment is carried out both deterministic and probabilistically to cover the full range of uncertainties and the impact on economic decision-making parameters for the pre-investment proposal.

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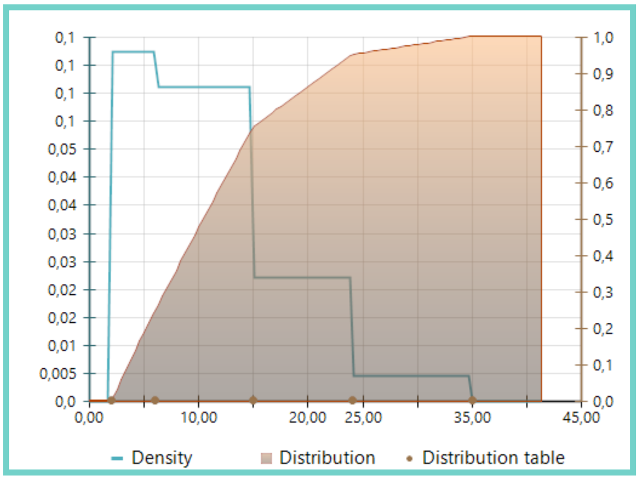
Based on the geological model analysis, it was identified the possibility of compartmentalization, partial transmissivity between storage site compartments, and no compartmentalization, bringing different pressure and limitation conditions. Base on those 3 cases, dynamic simulation and risk analysis, it has been defined a range of estimated capacity in Lopin structure between 2 Mt and 35 Mt, with an injection profiles and storage site management have been selected accordingly ensuring safe operation (injection rate limited by maximum reservoir pressure). In particular and describing these 3 situations by ranges of estimated capacity, Ebro Basin scenario is defined by these 3 cases:

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

Table 5.28 Scenario for the Ebro Basin CO_2 project

And cover, for the probabilistic approach by the following distribution of estimated capacity:



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

Figure 5.24: Estimated capacity distribution and cumulative distribution for Lopin structure.

It is assumed that CO_2 will be transported in dense phase to the injection facilities. All monitoring infrastructure implemented during the pilot will be expanded at this stage and adapted a total injected volume, including at least one observation well, and seismic, pressure and environmental monitoring. Finally, once the usable storage capacity is exhausted, the well(s) will be safely abandoned and the site will enter a long-term post-closure monitoring phase (decades) to confirm the permanent stability of the stored CO_2 in accordance with applicable regulations. As based case, the commercial configuration will rely on two injection wells operating in parallel on the order of 15 Mt of CO_2 over 30 years and 0.5 CO_2 Mt/year injection rate per well. To continuously transport half a million tonnes of CO_2 per year, a dedicated pipeline could be constructed from the capture plant to the storage site.

The capacity range compiles the potential compartmentalization of the reservoir (limited to 7 Mt); the base case studied and 3D simulated dynamically (covering between 7 and 15 Mt); and the optimistic case of no-compartmentalization and evaluated by 1D risk modelling (until 35 Mt). Maximum reservoir

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pressure and injection profile have been defined specifically for each of those ranges and referred in this text as Case 1, Case 2 and Case 3, respectively.

As an example, for the 14.9 million tonnes case, operation site covers 30 years through two wells. The design considers either simultaneous or alternating injection, with rates of approximately ~0.25 Mt/year per well. Updated dynamic models confirm that the reservoir can accommodate this volume without exceeding the fracture gradient (~0.17 bar/m). The maximum predicted overpressure is 60–70 bar in the worst case, with adaptive management in place to avoid interference between wells. The CO_2 plume extends to a radius of up to 2.5–3 km per well, covering up to 15 km². In the long term, CO_2 is immobilized through dissolution and residual trapping. A post-injection monitoring period of at least 20–30 years is envisaged, in accordance with the European Geological Storage Directive.

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

The duration of the commercial phase depends on the estimated capacity. Injection profile for the 5Mt, 14.9 Mt and 25 Mt are presented Fig 5.25.

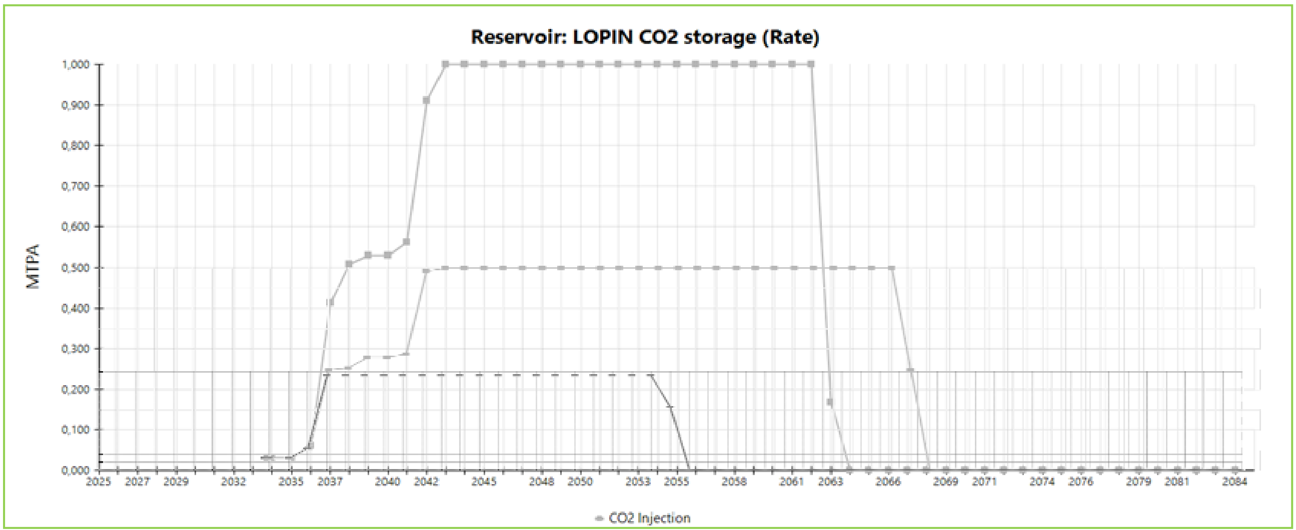

Figure 5.25: CO2 Injection profiles proposed for 5 Mt (1 well, 0.25 MTPA plateau), 14.9 Mt (2 wells, 0.5 MTPA plateau), and 25 Mt (2 wells, 1 MTPA plateau) of estimated capacity for the full life cycle.

Cases description for each capacities range is summarised on Figure 5.26.

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CASE	Capacity	Exploration	Monitoring	Injector wells	Injection rate	Deterministic case
Cases 1	Between 2 and 7 Mtonne	2D seismic + 1 exploration well	Baseline + 1 Injector sensors+ 1 water well + microsismisity+ inSAR+ CO2 soil	1	0.03 Mt/year @ 3 years; 0.25 Mt/year thereafter.	5 Mt Facilities CAPEX. 7 M€; OPEX, 3.5 M€; Abandonment: 5.6 M€ Baseline: 0.48 MM€
Cases 2	Between 7 and 15 Mtonne	2D seismic + 1 exploration well	Baseline+Injector sensors+ 2 water well + microsistisity+ inSAR+CO2 soil	2	0.03 Mt/year @ 3 years; 0.25 Mt/year thereafter.	14.9 Mtonnes Facilities CAPEX. 17 M€; OPEX, 4 M€; Abandonment: 7.5 M€ Baseline: 0.68 MM€
Cases 3	Between 15 and 35 Mtonne	2D seismic + 1 exploration well	Baseline+ Injector sensors+ 2 water well + microsistisity+ inSAR+ CO2 soil	2	0.03 Mt/year @ 3 years; 0.5 Mt/year thereafter.	25 Mtonnes Facilities CAPEX. 20 M€; OPEX, 5 M€; Abandon: 8.5 M€ Baseline: 0.8 MM€

Figure 5.26: Cases description for 5 Mt, 14.9 Mt and 25 Mt estimated capacity of Lopin for the deterministic evaluation

5.3.1.1 *Monitoring Plan (MMV)*

The MMV plan is 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.

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

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

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

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

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

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

MMV Plan is described on the D4.11. For the economic evaluation, those elements have been grouped as baselines; sensors in wells; groundwater aquifer wells; and seismic control. Provided elements and costs have been adapted to capacity range- for example, 4D seismic survey is applied if capacity is higher than 15 Mtonnes, and 2D seismic survey is applied when estimated capacity is lower than 15 Mtonnes.

5.3.2 Proposed planning

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

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

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

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

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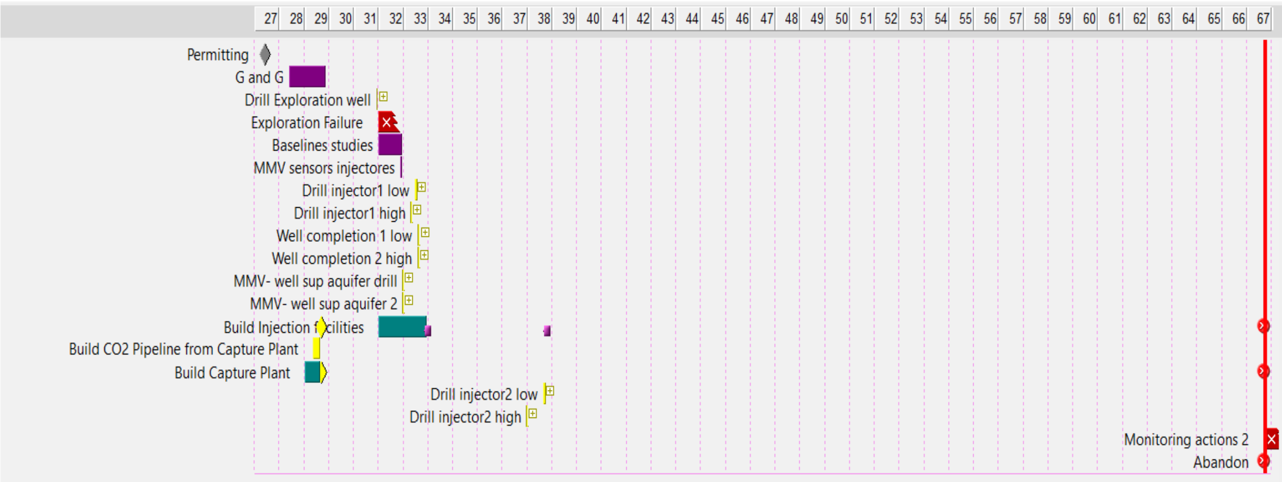
supply for the pilot (e.g. potential agreements with regional cement or chemical plants) will also take place during this stage.

Figure 5.27: Activities schedule for the full life cycle evaluation



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

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

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

Following completion of the pilot injection (3 years), the project enters a period of comprehensive results analysis. Technical teams will compare observed data (reservoir pressures, CO_2 plume migration, microseismic events, etc.) with prior predictions. If storage performance is favourable—i.e. confirming good injectivity, absence of leakage, and controlled seismicity—the project will move forward to plan commercial-scale expansion. This will involve preparation of a Final Investment Decision (FID) report consolidating pilot learnings, an updated economic and financial assessment

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(Canteli et al., 2025b, D4.9), and a detailed plan for the next phase. At this intermediate stage, the geological storage concession at commercial scale will also be pursued, requiring expansion or adaptation of existing permits to cover larger volumes and longer injection periods (likely including a new Environmental Impact Declaration for the 30-year industrial phase). Based on similar experiences, a timeframe of approximately two years is estimated to secure authorizations and financing for the commercial phase following the pilot. During this period, the pilot well may remain under observation (with no further CO_2 injection), while continuing early post-injection monitoring to extend the pressure fall-off and plume evolution datasets.

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

For the probabilistic analysis of Ebro Basin case, costs (CAPEX, OPEX, ABEX), construction times, dependencies and expected success (Pg, Pe) have been defined. Parameters and distributions are shown in the Table 5.29.

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

Table 5.29 Geological success probability (Pg) and pilot success probability (Pe) values considered for the 3 probabilistic scenarios analysed.

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

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

5.3.3 Timing and Cost description of the model

According with proposed schedule, the different phases, interaction and dependencies are described. CAPEX, OPEX and duration have been defined for each of them, providing a fix value for the deterministic cases and a distribution for the probabilistic evaluation. In most cases, this distribution is defined as triangular as -20%, +30% from fix value. CAPEX and OPEX are defined at 2025.

Facilities cost have been obtained by Qestor software for the 3 different cases. Well costs and MMV cost are described with more detail.

Phase	Description / Values	Distribution
Exploratory permit request	Requested on 06/01/2027.	Triangular distribution: 04/01/2027 – 06/01/2027 – 07/01/2028.
Permit approval	Granted 6–16 months later, most likely 12 months.	Triangular distribution: 180 – 365 – 456 days.
G&G (Geology & Geophysics)	Starts after permit approval. Includes preparation, survey, processing.. Deterministic value: 6.25 M€	Duration triangular distribution: 15 – 18 – 24 months. CAPEX (M€): 5–9.5 M€ (uniform).
Exploratory well + injection tests	Starts after G&G. Total duration (site selection, design, tendering, drilling): Drilling: 1 month; injection test: 1 month. Rig cost: 65,000 €/day	Duration Exploration: triangular 15 – 24 – 30 months. Duration drilling: duration 50–60–90 days Well costs (including tests): 7.4–9.1–12.6 M€.
Exploration success rate	Base case: 0% failure. Case 2: 60% success. Case 3: 54% success.	Binomial
Baseline studies	Only if exploration succeeds. Duration 12 months. Cost 0.3 M€	Duration triangular: 9.6-12-18 months
Injectors	Number depends on estimated capacity: 1 or 2 wells. If a second well is needed, drilled within 5 years. Costs validated by Heyco (Spain, 2024).	Triangular distribution: CAPEX per well: drilling (5.6; 7; 13.2 M€), completion (2.1; 2.8; 4.2 M€), MMV sensors (0.8; 1; 1.5 M€). OPEX: 0.8–1–1.5 M€/year, incl. 0.35 M€ monitoring.
Phase 1 – Pre-commercial pilot	Duration 3 years. Max injection 100,000 t (legal limit). Injection rate: 0.3 Mt/year.	
Phase 2 – Commercial	Continues until 95% of estimated capacity is injected. Injection configuration: (1) 2 to 7 Mt → 1 injector @ 0.25 Mt/year. (2) 7 to 15 Mt → 2 injectors @ 0.25 Mt/year each. (3) 15–35 Mt → 2 injectors @ 0.5 Mt/year each (most favorable case).	
Shallow aquifer wells	1 or 2 monitoring wells if capacity is higher than 7 Mt. Cost: 0.1 M€/well.	
Injection facilities	Start after exploration success.	Duration triangular 18 – 24 – 30 months. CAPEX (7; 17; 25.5 M€) correlated with capacity. OPEX (3.5; 4; 6 M€) correlated with capacity.
4D monitoring	Activated at year 4 if a second injector is drilled.	
Abandonment	Triggered at 95% of capacity.	Triangular distribution: CAPEX: (5.6; 7.5; 9.4 M€).
Post-abandonment monitoring	Not included (costs >10 years, no depreciation impact).	
Capture plant & pipeline	Considered only for CO_2 supply; no costs or dependencies included.	

5.3.3.1 *Well costs*

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 3 MUSD (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 1M USD (0.92 M€) is assumed.
- The daily rig rate is based on Repsol similar projects and a query to procurement department.

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- 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. Therefor the cost is not included in this T&C estimate.
- For the P&A the following assumptions apply (Figure 5.28):

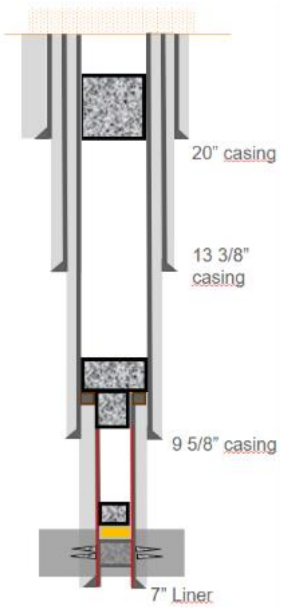

Figure 5.28: well P&A assumptions

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

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- 100m cement plug settled above liner hanger.

- **Wellhead Removal**:
  - 100m surface plug placed up 100m below ground.

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 5.30: Injection well time & cost estimate

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.

- No T&C is estimated for the Pad preparation and all civil works associated with it.
- For Project Management 500K$ (460K€) is assumed.
- For 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

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 5.30).

5.3.3.1.1 MMV Plan costs

The MMV Plan Objectives are:

- Demonstrate containment of CO_2 within the authorized storage complex, with auditable evidence for regulators.

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- 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.
- 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.

MMV plan costs are summarized on Tables 5.31, 5.32 and 5.33.

Table 5.31: Cost for element of the MMV Plan

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).

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Table 5.32: Unit Cost for activity

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.
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 5.33 Summarizes the unit costs (CAPEX, O&M, or per-campaign) for the MMV programme.

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

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Closure – 2 years (EUR)	312,336	361,672	361,672	4,621,672
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

5.3.3.2 *Costs and timing distribution considered*

For those cases considered relevant for the probabilistic analysis, triangular or uniform distributions have been defined. Table 5.34 collects those distributions.

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

Table 5.34: Defined distribution for selected CAPEX, OPEX and construction time

5.3.4 Economic assessment

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

- Definition of estimated capacity distribution, based on geological uncertainties and possibility of compartmentalization. A range between 2 Mt and 35 Mt has been considered with P75= 14.9 Mt. The deterministic evaluation is based on 5 Mt, 14.9 Mt and 25 Mt.
- Definition of exploration phase: geological and geophysical campaigns, and exploration well and test.
- Definition of injector well(s) and injection profiles, for pilot phase (1 well, 0.03 MTPA for 3 years) and for commercial phase (table XX). Well costs including drilling and completion).

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- Definition of the injection facilities: capture plant and transport are out of the study. Surface facilities (reception, compressor and injectors) are defined based on maximum handled CO_2 volumes.
- Schedule (or planning): the different activities carried out in time, considering dependency between activities. Uncertainty (delays, advances) are included for key activities (permitting process, drilling time, facilities building) by required time distribution. The considered activities are exploration permit application and granting, exploration phase, baseline measurements, drill and completion wells, injection facilities construction, MMV plan application, and abandonment when the 95% of total estimated capacity is reached.
- Chance of geological success (Pg) and chance of exploitation success (Pe): for the probabilistic approach, a chance of geological success Pg=0.6% is applied (i.e. after exploration well, 60% of cases pass to next phase and 40% the project is abandoned); and after pilot phase, a change of exploitation success of Pe=0.54% is applied (i.e. after 3 years of pilot operation, 54% of cases pass to commercial phase and 36% project is abandoned). Pg and Pe have been defined bases on existing information and internal experts panel definition.
- Economic model: It is based on an economic cashflow model, where it is assumed that revenues correspond to the value of tonnes of CO_2 stored per year at the EU ETS price.
- Price forecasts (base, low and high) have been assumed. Other financial parameters of interest are discount rate (9%) and inflation (2.2%). Results are discounted to 2025.
- Costs (CAPEX and OPEX) have been defined as Class IV at 2025 and, for distribution definition, considered triangular distribution with real cost 2025 as centre point (-20%, +30%).
- Deterministic results: they are indicated for an estimated capacity of 5 Mt, 14.9 Mt; and 25 Mt.
- Probabilistic results: Monte Carlo with 10,000 simulations/5000 for comparative criteria.
- Sensitivity analysis has been made to the distributions of the capacity; a percent to be received per tonne (storage fee).

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

Case	CAPEX (Million€)	OPEX (Million€)	Max Cash out (Million€)	NPV (9, 2025, BP) (Million€)	NPV (9, 2025, LP) (Million€)	NPV (9, 2025, HP) (Million€)	Breakeven (€/tonne)
5 Mt	65	135	-37	82	16	165	**73**
14,9 Mt	99	275	-49	178	51	337	**42**
25 Mt	105	280	-64	382	143	690	**27**

Table 5.35 Deterministic results for 5 Mt, 14.9 Mt and 25 Mt estimated capacity

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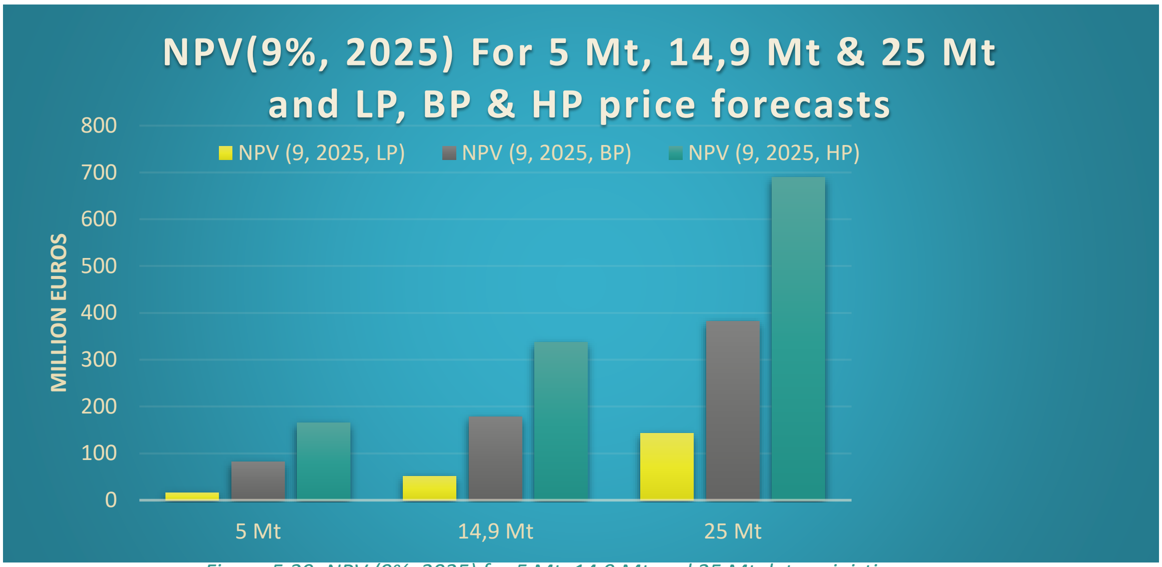

Figure 5.29: NPV (9%, 2025) for 5 Mt, 14.9 Mt and 25 Mt deterministic cases

Based on the **probabilistic analysis**, the cases have been analysed: (1) Considering success case (i.e. Pg=1 and Pp=1); (2) considering Pg=0.6 and Pp=1; and (2) considering Pg=0.54 & Pg=0.46. All cases have been analysed for the full life cycle and defining parameters distributions for key elements in CAPEX, OPEX and timing (Table 5.29). Results are shown on Table 5.36, Table 5.37 and 5.38, respectively.

In the first case (1) in which all starting evaluations go throw exploration, pilot and commercial phase, results on NPV for all considered prices are positive (except the very low tale of the low price, <P10) giving very good overview of a solid case (Table 5.36). However, it should be considered that the assumption of giving ETS price per tonne storage it is just for a common reference and, for a business case evaluation, the ETS price per tonne should cover capture, transport and storage phases.

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

Table 5.36 NPV (9%, 2025) and abandonment year results for the 3 CO2 prices forecast (BP, LP, HP) and success case (Pg=1 & Pe=1) based on probabilistic analysis.

In the second case (2), the probabilistic economic results for the full life cycle and based on base price evaluating the geological success (Pg=0.6 & Pe=1), the cumulative distribution shows a P50 of 70 MM€ (mean value of 94 M€) with negative values in the low side of the distribution (P<15%). Similar results are obtained high price case although, for Low Price case, it is a 48% chance of negative NPV (table 5.37).

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Table 5.37 NPV (9%, 2025) and abandonment year results for the 3 CO2 prices forecast (BP, LP, HP) and Pg=0.6 & Pe=1 based on probabilistic analysis.

Pg=0.6; Pe=1	Unit	Mean	P10	P50	P90	Min	Max
Abandonment Year BP		2048	2032	2054	2064	2031	2073
Abandonment Year HP		2048	2032	2054	2064	2031	2073
Abandonment Year LP		2048	2032	2053	2063	2031	2073
NPV 9- BP	M€	94	-17	70	311	-20	426
NPV 9- HP	M€	183	-24	150	562	-29	764
NPV 9- LP	M€	22	-17	5	123	-20	167
Total CO2 injected	Million tonnes	6	2	5	16	2	33

Finally, Case 3 considers both the change of geological success (after exploration results) and the change of exploitation success, after the pilot results (Table 5.38). In this case, despite of the negative NPV distribution for perceptible P50 or lower, the upside gives very good results for the 3 forecast prices with similar investment needs.

Table 5.38 NPV (9%, 2025) and abandonment year results for the 3 CO_2 prices forecast (BP, LP, HP) and Pg=0.54 & P2=0.46 based on probabilistic analysis.

Pg=0.56; Pe=0.42	Unit	Mean	P10	P50	P90	Min	Max
Abandonment Year BP		2039	2030	2036	2059	2030	2072
Abandonment Year HP		2039	2030	2033	2059	2030	2072
Abandonment Year LP		2039	2030	2034	2059	2030	2071
NPV 9- BP	M€	36	-21	-16	185	-25	463
NPV 9- HP	M€	76	-26	-8	331	-32	796
NPV 9- LP	M€	10	-23	-6	68	-27	207
Total CO2 injected	Million tonnes	3	0	5	16	0	33

It has been also analysed the impact of first injection date (delays and fast-tracks permits, construction, deliveries, …). If the deterministic cases define the expected first injection date at 2033, considering the impact of different events it can be expected a 6-year range, with an estimated impact of a 10% reduction of NPV value for 1 year delay only due to permitting process. (Figure 5.30).

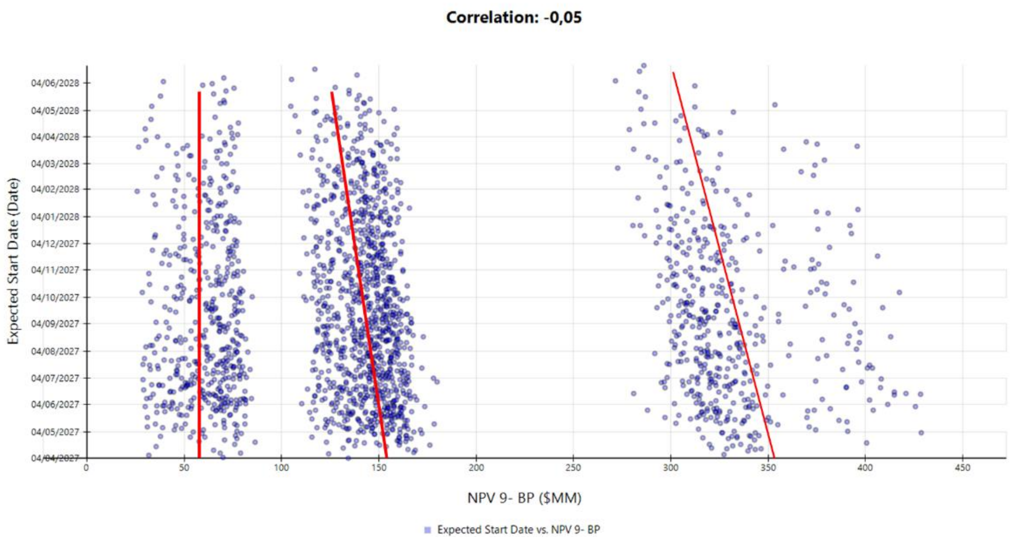

Figure 5.30: Impact on permitting delay on NPV (9%, 2025)

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In conclusion, the analysis incorporating both Pg = 0.54 and Pe = 0.46 provides greater clarity regarding the potential of the Lopin and Ebro Basin proposal. Under this combined failure-case scenario, the resulting distributions show negative values below the P50 percentile across all forecast price assumptions. Nevertheless, the expected outcomes remain highly attractive: in at least 50% of cases and across all three price scenarios, the risked NPV (9%, 2025, BP) exceeds €200 million, which can be considered very promising. It should be noted, however, that the use of the ETS price per tonne of storage is intended solely as a reference. For a proper business case assessment, the ETS price per tonne would need to cover the full capture, transport, and storage value chain.

5.4 Upper Silesia (Poland)

The simplified economic assessment aims to provide an indicative evaluation of the financial feasibility of the proposed CO_2 storage development in the Pągów-Milanów area (Upper Silesia Basin), structured as a pilot phase followed by a potential commercial phase. The assessment covers the full CCS chain (capture, transport, injection and monitoring) over a 33-year operational horizon, including at least 20 years of post-closure monitoring in line with Polish Geological and Mining Law requirements. The analysis is based on a pre-FEED level of maturity and uses simplified cost estimation methods. The purpose of this section is to summarise the key economic drivers, assumptions and results relevant for strategic decision-making.

5.4.1 Key assumptions

The reference scenario assumes:

- Pilot phase: 30 kt CO_2/year for 3 years.
- Commercial phase: 300 kt CO_2/year for 25 years.
- Total injected volume: approx. 7.5 Mt over both phases.
- Estimated storage capacity of the selected structure: approx. 31 Mt
- Discount rate applied in calculations: 9%.
- 20% CAPEX contingency due to low project maturity.

Three CO_2 price scenarios were considered (low, base and high), reflecting different trajectories of EU ETS allowance prices. Electricity prices and inflation were included based on available national projections at the time of modelling. No dedicated public support scheme for CCS in Poland was assumed in the base case.

5.4.2 CAPEX and OPEX structure

Capital expenditure is considered for two phases: pilot and commercial.

The pilot phase CAPEX includes:

- 3D seismic surveys and modelling,
- preparation of technical documentation and permits,
- drilling and completion of one injection well,

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- limited surface infrastructure.

In the commercial phase, CAPEX increases substantially due to:

- construction of an approximately 80 km pipeline,
- expanded surface facilities,
- additional infrastructure and integration systems.

Pipeline construction constitutes the dominant investment component in the commercial configuration.

Table 5.39 Estimation of CAPEX for Upper Silesia scenario

Item	Unit	Amount
3D seismic research	mln EUR	2.80
Modelling, technical documentation, permits and administrative decisions (including environmental decisions)	mln EUR	2.00
Wells - drilling + completion	pcs	1.00
	mln EUR/pcs	7.20
	mln EUR	7.20
Pipeline	km	80.00
	mln EUR/km	2.00
	mln EUR	160.00
Land, infrastructure on the ground surface - pilot phase	mln EUR	4.50
Land, infrastructure on the ground surface - commercial phase	mln EUR	9.00

Operating expenditure is driven primarily by:

- CO_2 capture cost, which represents the largest share of total CCS chain cost.
- Transport cost, differing significantly between road (pilot) and pipeline (commercial) modes.
- Injection energy consumption, mainly electricity for compression and pumping.
- Monitoring costs, including reservoir and surface monitoring during operation and post-closure.
- Personnel, maintenance, local taxes and insurance.

Monitoring represents a structurally relevant long-term cost component due to statutory post-closure obligations.

Table 5.40 Estimation of OPEX for Upper Silesia scenario

Item	Unit	Amount
Duration - pilot	year	3
Duration - commercial	year	25
Electricity - pilot	MWh/3 years	154.03
	MWh/year	51.34
Electricity - commercial	MWh/25 years	12 835.83
	MWh/year	513.43
Monitoring	mln EUR/year	4.50
Salaries	posts/shift	4
	shifts	3
	EUR/month	2 000
	EUR/year	288 000
Local taxes, insurance	% CAPEX	2%
Maintenance and repairs - pilot phase	mln EUR/year	0.09
Maintenance and repairs - commercial phase	mln EUR/year	0.18
Cost of CO_2 capture	EUR/t CO2	12.00
Cost of CO_2 transport (road)	km	80.00
	EUR/km/t CO2	0.23
Cost of CO_2 transport (pipeline)	km	80.00
	EUR/km/t CO2	0.01
CO_2 injection - pilot	t/year	30 000
CO_2 injection - commercial	t/year	300 000

The simplified assessment assumes that the primary economic benefit arises from avoided costs of EU ETS emission allowances. No additional revenue streams (e.g. CO_2 utilisation markets, national

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subsidies or carbon contracts for difference) were included. Therefore, project viability is highly sensitive to EU ETS price trajectory.

In the absence of dedicated national support mechanisms, the business case relies predominantly on sufficiently high and sustained carbon prices.

5.4.3 Economic results

Table 5.41 Economic results for pilot phase

PILOT PHASE						
Scenario	**CAPEX**		**OPEX**		**NPV**	**IRR**
	mln EUR	**EUR/t CO2**	**mln EUR**	**EUR/t CO2**	**mln EUR**	**%**
Scenario 1 - base CO_2 price	21.07	234.13	26.31	292.32	-27.28	non-existent
Scenario 2 - low CO_2 price					-28.73	non-existent
Scenario 3 - high CO_2 price					-21.56	non-existent

Table 5.42 Economic results for pilot and commercial phase

TOTAL - PILOT + COMMERCIAL PHASE + MONITORING (20 years)						
Scenario	**CAPEX**		**OPEX**		**NPV**	**IRR**
	mln EUR	**EUR/t CO2**	**mln EUR**	**EUR/t CO2**	**mln EUR**	**%**
Scenario 1 - base CO_2 price	254.70	33.56	725.10	95.53	-62.67	non-existent
Scenario 2 - low CO_2 price					-142.03	non-existent
Scenario 3 - high CO_2 price					110.10	16,3%

The results indicate that the pilot phase alone is not economically viable under any CO_2 price scenario, with negative NPV and non-existent IRR. When both pilot and commercial phases are included, the project becomes economically viable only under the high CO_2 price scenario. However, under base and low-price scenarios, NPV remains negative over the full project horizon.

This result confirms that the pilot phase should be understood as a risk-reduction and feasibility demonstration stage rather than a stand-alone investment project.

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5.5 Macedonia Basin (Greece)

5.5.1 Scenario description

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

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

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

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

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

5.5.2 Proposed development

1. *Capture*

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

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

2. *Transport*

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

From an operational perspective, CO_2 transport is expected to occur in dense or supercritical phase, typically above 80 bar, ensuring flow stability and minimising the risk of phase transitions. Upstream conditioning is required to meet transport specifications, including dehydration to avoid corrosion and hydrate formation, as well as compression to match pipeline and injection pressure conditions. Pressure losses along the transport system must be explicitly accounted for, particularly in relation to injection pressure constraints imposed by the reservoir (Table 5.43)

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

Table 5.43 Key transport design parameters for the Mesohellenic CCS system

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3. *Storage*

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

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

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

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

Table 5.44 Key storage system parameters and operational constraints

5.5.3 Proposed planning

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

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

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

The full-scale development phase is based on the progressive expansion of both subsurface and surface infrastructures. Additional wells are introduced to distribute injection spatially, while transport capacity is increased to accommodate larger CO_2 volumes from external sources. The use of multiple stratigraphic intervals allows further optimisation of storage efficiency and pressure management, enabling the system to operate at higher injection rates without exceeding operational thresholds (Table 5.45).

Phase	Main activities	Key uncertainties addressed	Technical objective
Site characterisation	Data integration, additional measurements, reservoir modelling	Permeability distribution, reservoir connectivity, structural complexity	Define injectivity and pressure limits
Pilot injection	Controlled injection tests, pressure monitoring, model calibration	Injectivity, pressure propagation, boundary conditions	Validate dynamic reservoir behaviour
Early operation	Limited well deployment, initial transport infrastructure	Well performance, short-term	Establish stable injection regime

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		pressure response	
Expansion phase	Additional wells, multi-layer injection, increased transport capacity	Long-term pressure evolution, reservoir interaction	Scale injection while maintaining pressure control
Full-scale operation	Integrated system operation with external CO_2 supply	System-wide performance and operational optimisation	Maximise storage utilisation under safe conditions

Table 5.45 Phased development plan and associated uncertainties

5.5.4 Economic assessment

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

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

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

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

Parameter	Indicative value / range	Economic implication
Total CAPEX (full chain)	~600–800 M€	Includes capture (external), transport and storage

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

Table 5.46 Key economic parameters and assumptions

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

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

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

6. Conclusions

6.1 Paris Basin (France)

The local scenario i.e. using the CO_2 from the plant is less economically attractive than the external scenario i.e. purchasing the CO_2. The main drivers are the difference between the CAPEX of the compressor versus the purchase cost of the CO_2. There is however a caveat to the external CO_2 related

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to the availability of such quantities of CO_2 in the current market. Such availability is currently not possible within the French or European market which are mainly driven by offtake long term contracts.

Table 6.1 estimates the relative difference of onsite scenarios with respect to offsite scenarios.

Scenario	P10	P50	P90
Local CO_2	-15.2%	3.6%	26.1%
External CO_2	-4.6%	7.4%	20.9%

Table 6.1 Distribution of the relative difference between offsite and onsite scenarios (M€$_{2025}$)

The onsite scenario, where the well-head is within or near the plant and the well is strongly deviated, tends to be less economically attractive than offsite scenario where the well-head is about 3 kilometres away from the plant and the well is slightly deviated. Given the cost uncertainty level (Class IV), there is however a range of probability where the opposite is true:

- below P41 for the local CO_2 scenario
- below P22 for the external CO_2 scenario

6.2 Lusitanian Basin (Portugal)

The economic assessment of the Lusitanian Basin pilot indicates a high-cost, low-revenue profile, consistent with an early-stage offshore CO_2 storage demonstration. The most-likely total investment (CAPEX + OPEX + ABEX) is approximately €98 million, with a P50 value of ~€104 million and a wide uncertainty range reflecting the pilot nature of the project.

Costs are dominated by drilling and completion, subsea systems, and 3D seismic acquisition, while OPEX is mainly driven by CO_2 transport, shipping and injection operations. Seismic costs are treated entirely as CAPEX and represent a significant upfront investment required for site qualification and monitoring readiness.

Overall, the Lusitanian Basin pilot should be viewed as a strategic de-risking and learning investment, essential to reduce geological and monitoring uncertainty and to enable a potential future commercial-scale CCS development, where costs could be amortized over significantly larger injection volumes.

6.3 Ebro Basin (Spain)

The economic evaluation assesses three development options based on estimated storage capacity ranges (2–7 Mt, 7–15 Mt, and 15–32 Mt), with deterministic cases analysed at 5 Mt, 14.9 Mt, and 25 Mt. Storage capacity is the main source of uncertainty and the dominant driver of economic performance, strongly influencing CAPEX, OPEX, cash outflows, and NPV, which remains positive under the EU ETS in all cases. Probabilistic analysis distinguishes two investment regimes (below and above 7 Mt) and three economic outcome groups, capturing the impact of uncertainty and schedule delays. Break-even storage fees define the viability of commercial scenarios, with ranges of 20–40% that may limit future development potential.

Based on the results, strong case is defined on the upside of the estimated capacity distribution, for all different prices forecasts, which brings an opportunity if this possibility of upside of capacity is verified.

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6.4 Upper Silesia (Poland)

In the current Polish context, characterised by the absence of operational CO_2 transport infrastructure and limited market experience with CCS, the concentration of financial risk in the pre-investment phase represents a substantial barrier.

The simplified assessment suggests that commercial viability is conditional upon high carbon prices and scale effects. Consequently, the pilot phase is more appropriately positioned within research and innovation funding schemes aimed at reducing technical and regulatory uncertainty before private capital engagement.

Overall, the project's economic feasibility depends on the successful transition from pilot to commercial scale and on favourable long-term carbon pricing conditions.

6.5 Wester Macedonia (Greece)

Taking into account the economic assessment carried out on D4.9, and reviewed in light with last studies, the project aims to develop a CO_2 storage capacity of 90 million tonnes, with an estimated capital expenditure of €301 million plus a 15% contingency, based on 2021 cost assumptions adjusted for a 2.2% annual inflation rate and a planned start in 2025. Key upfront investments include a 2,100 km^2 seismic survey costing €21 million and the drilling of three medium-depth wells with a total cost of €43.2 million, alongside additional expenditures for processing, interpretation, environmental assessments, and engineering, procurement, and construction. Operating expenditures are expected to amount to around 8% annually, covering administrative and social engagement costs, while the project timeline anticipates first CO_2 injection in Q1 2033. Financially, the project assumes a CO_2 injection rate of 3 million tonnes per year over 30 years, a CO_2 price of €75 per tonne, and a 10% discount rate, resulting in an estimated net present value of €991 million, indicating strong economic viability. Long-term cost efficiency is expected to be enhanced through the development of new, dedicated CO_2 pipelines and the integration of local CO_2 utilization options, which could reduce transport costs and create additional revenue streams.

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