WP4 -Deliverable 4.9

Economic evaluation of alternatives and prioritisation results

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2. Executive summary

Based on this work package previous reports (D4.1 *Methodology for alternatives definition, prioritisation, and selection*; and D4.2 *Conceptual scenarios definition to enable decision support*), each region has defined (elements, activities, and schedule) selected scenarios, reviewed them, and carried out a techno-economic evaluation with the goal of comparing region alternatives and selecting the optimum development scenario for Paris Basin, for Lusitania Basin, and for Ebro Basin; and, with lower detail but following the same approach, for Silesia Basin and Macedonia Basin. Those optimum developments will be built and evaluated in detail by each region team during next months, being the basis for the final investment decision report.

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

Although it is not a compared evaluation between regions, it was proposed a common economic parameter for the economic evaluation (ETS market CO_2 price forecast, discount rate (9%), electricity price, inflation rate (2,2%), 20% contingency, and year of reference (2025)).

The economic evaluation of Portuguese and Spanish region is based on pre-commercial and commercial development with inflated and discounted cash-flow for the full life cycle; the French case, however, is based only in pre-commercial (pilot) phase and the economic evaluation is based in required investments at 2025 money (no CO_2 storage accounted). Poland and Greece follow similar approach as it was done in the Strategy CCUS project.

Paris Basin (France): it is focused on a pilot project with a close-by emitter. For the pilot scenarios considered, the economics are exclusively based on CAPEX analysis. The time frame of this pilot case is driven by the permitting process in France. The scenarios evaluation is based on transport possibilities and surface/subsurface limitation due to the proximity of installation -including water well disposal from local industry and a railway-. A short distance transport was considered either by pipeline or by trucks, as well as vertical or deviated well. The injection rate planned is 0.3 Mtpa with maximum injection limited by pilot permitting (100.000 tonnes). The transport CAPEX is 15.7 M EUR for pipeline and 25.7 M EUR for road transport. The selected scenario considers a short distance pipeline transport when the injection well is located about 3 km away from the emitter, and a deviated well.

Lusitanian Basin (Portugal):

For the pilot phase, CO_2 sources are assumed to be from the closer points (cement/lime, glass, and paper and pulp industries), 50 to 80 km from the storage site. The pilot is designed to inject CO_2 at a rate of 90 kt per year, with a total injection volume of 270 kt over three years.

Therefore, to assess the CAPEX of the different transport chains, estimations only considered transport from the local emitters to the Figueira da Foz port. Details on the capture and conditioning of CO_2 at the sources were not considered in this project.

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The choice of transport mode depends on the project phases. Among the scenarios considered, train transport and shipping are proposed only in the pilot Phase I (fast-track development at minimal cost to prove technical feasibility). The commercial injection (Phase II) scenario prioritises offshore pipeline transport due to its operational and logistical advantages.

Ebro Basin (Spain):

Ebro basin scenarios are based on a pre-commercial phase (pilot scale) and a commercial phase with full life cycle evaluation under the common economic frame and approach. The evaluation includes the storage site operation; that is, neither capture nor transport is included. It is assumed CO_2 stream impurities are compatible with the Lopín storage site and there are no limitations due to CO_2 quality. Selected scenarios have been described, economically evaluated for the full life cycle, and economic parameters compared to select the optimum option. The breakeven price (storage fee) has been calculated for the different scenarios as a percentage of the ETS market price forecast as an indicator of project viability.

The evaluation has tried to identify the better strategy to apply considering current information available. The main uncertainty is the estimated capacity and whether or not existing compartmentalisation limits the maximum injection rate and total volume. Based on it, the evaluation shows economic results for NPV (9%, 2025) for the 2 Mt, 4 Mt, and 23 Mt cases, and identifies that NPV is highly dependent on storage prices and breakeven. Based on it, the Minimum Investment scenario is the most robust case for the different prices. Based on cash-flow, cash-out and flexibility, the Minimum Investment case presents lower initial investment and faster than the other two scenarios recuperation to a positive balance. In the long term, the Green Development shows better income results and positive parameters.

Upper Silesia Basin (Poland): A pilot-scale injection of about 30.000 CO_2t/y for three years, followed by a commercial phase of 300.000 CO_2t/y for 25 years, has been studied. The CO_2 emitters that could nowadays be interested in CO_2 sequestration are located at 30 to 80 km to the proposed injection site (30 Mt capacity).

Strategy CCUS project analysis has been used for cost estimation, considering one injection well only. In this region, they included capture, transport, and injection costs.

The scenarios presented in this region are based on the CO_2 pricing forecast (from years 2025 to 2057):

- Scenario 1: base CO_2 price = from 75 EUR/t (2025) to 130 EUR/t (2057)
- Scenario 2: low CO_2 price = from 75 EUR/t (2025) to 75 EUR/t (2057)
- Scenario 3: high CO_2 price = from 75 EUR/t (2025) to 230 EUR/t (2057)

The results show that the pilot phase could cost up to 45.51 MEUR. Adding to the pilot cost further commercial development and monitoring gives a cost of around 1,069.83 MEURD. The commercial development only provides positive results in the high CO_2 price scenario. This more optimistic scenario gives a NPV of 89.81 MEUR with an IRR of 14.6%.

Macedonia Basin (Greece): The Greek case shows a more general scenario considering emitters from Greece and nearby countries (Italy, Turkey, Bulgaria, ...). Nevertheless, the Greek facilities that could supply CO_2 to the storage complex are at 50 to 100 km. In this case, they have studied the capture, transport, and injection costs. The capture cost of the Ptolemaida V power plant is estimated to range between 150 and 350 MEUR. The pipelines needed to transport CO_2 to the storage site (Mesohellenic Basin, capacity about 90 Mt) could cost 142-186 MEUR. Three wells are included in the scenario. Roughly, a CAPEX 301 MEUR has been calculated for the storage site. 3 Mtpa injection rates for 30 years give a NPV of 991 MEUR (CO_2 price fixed at 75 EUR/t and 10% discount rate).

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3. Introduction

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). This deliverable describes the selection of this optimum development for each region based on the techno-economic evaluation of possible local scenarios and its ranking according to the objectives defined by each region.

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.
- Ranking scenarios according to results and region goals.
- Propose a final development for its pilot for further detail evaluation.

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. Considering the level of uncertainty at this stage, it is only possible to provide a general overview. Next phases of the study will provide an increased level of detail, enabling the economic evaluation of the pilots.

Besides, the economic evaluation depends on many external factors, such as CO_2 price, fiscal system, or state of the market. CCS is a relatively new technology, and only a few developments are available to follow as a model, costing reference or proposing a learning curve. On top of that, geological and technical uncertainties must be managed and evaluated.

Taking these in account, in the frame of PilotSTRATEGY, the economic evaluation will be carried out at two different levels for each regional pilot (FR, ES, PT) and focused on the first level for Poland and Greece:

- Level 1: Alternative-compared evaluation for each selected pilot, based on simplified models of applicable concept for the full lifecycle, and with a deterministic approach. The objective is to prioritise the alternatives defined for each region based on this economic evaluation (NPV, IRR, initial investment). A sensitivity analysis will be carried out to identify key parameters for cost optimization.

- Level 2: Detailed lifecycle economic evaluation of the final concept for each region considering probabilistic-economic evaluation of the full lifecycle and included subsurface uncertainties. A sensitivity analysis will be carried out for parameters: uncertainty impact, cost reduction and concept optimisation. A simplify tax regime frame will also be considered.

The proposed methodology looks for selecting the best option considering all these unknowns and uncertainties at this stage, based on the level 1 described earlier, with a coherent and consistent economic evaluation, cost allocation, economic scenario forecast, and selected criteria for alternatives prioritisation provided by *task 4.4. Economic evaluation*.

It must be mentioned that CCS development priorities and policies -in Europe and at the national level- have changed considerably from the time the proposal was written, and it has impacted and forced to clarify the final aim of each region. Therefore, the three main regions consider the possibility of a commercial development, and the term "pilot" becomes synonymous with pre-commercial development instead of "research facility". In addition, this commercial possibility is evaluated in the case of Portugal and Spain to have a more complete economic evaluation.

Coming back to the criteria for alternatives comparison, during July 2024 a workshop was organised with the objective of identifying those criteria by region (milestone MS20), understanding as **criteria for alternatives prioritisation those quantified or measured parameters** obtained during a techno-economic evaluation, key for a possible implementation, considering the main priorities of the region, and applicable to all regional scenarios. Those can be economical parameters (NPV, total investment), priorities-related (first injection date; local jobs), or based on limitations (water or electricity needs, for example). It can be different for each region, and 4 to 6 criteria are recommended.

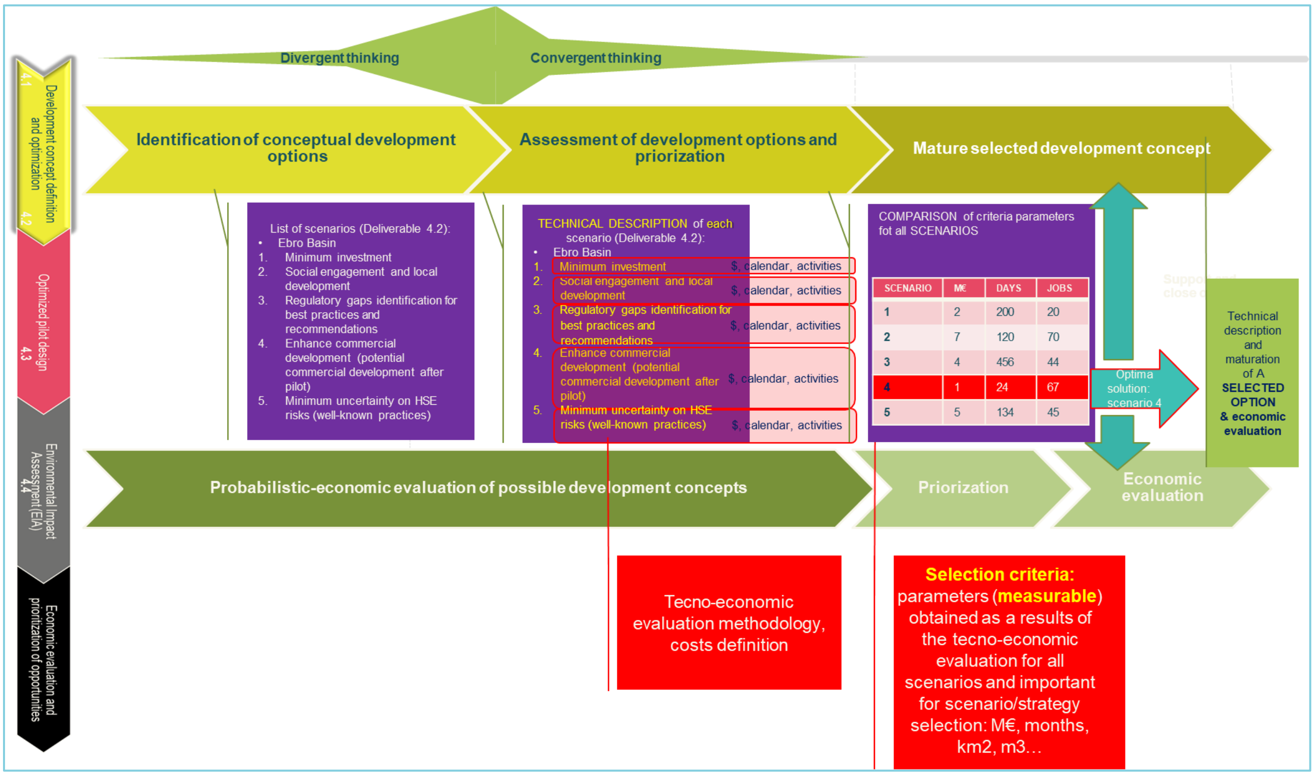

Figure 3.1: Proposed methodology for techno-economic evaluation of alternatives and prioritisation. Example based on Ebro Basin case.

During MS20 workshop, the following general criteria of interest were identified:

a) Pilot/pre-commercial phase:

1. Pilot total Investment or CAPEX. (M€)
2. Pilot Total duration (from exploration to production test). (Months/Years)

3. Land t occupied temporarily (access authorizations, area needed for seismic campaigns…). (Km^2)
4. Water needed (intense use?) (m^3)
5. CO_2 needed. (tonnes)
6. Power consumption (KWh)
7. Personnel needs (local workers/direct jobs per year)

b) Commercial/operating phase:

1. Project Total Investment (CAPEX). (M€)
2. Total duration (from injection to abandonment) (Years)
3. Total surface occupied (permit). (Km^2)
4. Water needed (m^3)
5. CO_2 storage. (Million tonnes)
6. Power consumption and source (fossil/renewable) (Kwh)
7. Personnel needs (local workers/direct jobs) (Number of local workers)
8. Financial results (NPV, IRR)

Each region has selected the most appropriate ones to their cases.

In summary this document pretends to state:

- Common economic frame and approach
- Techno-economic description for selected scenarios (actions, schedule, costs)
- Economic evaluation of scenarios and prioritization
- Optimum development concept to final investment decision

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 economical evaluation to facilitate evaluation, 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 common economic parameters are:

- **Year of reference**: 2025
- 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**.
- **Discounted rate**: 9%[1]
- **Inflation rate**: 2.2%[2]

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[1] 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)

[2] 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

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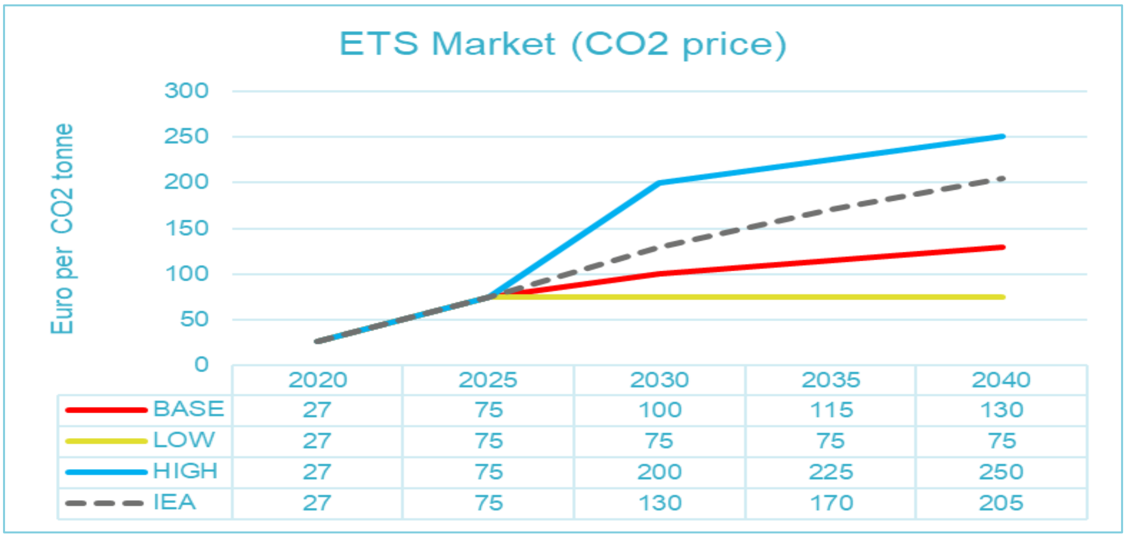
- **Currency**: Euros. Exchange rate for other currency at first working day of September 2024. (i.e. 2nd September 2024). For reference, 1 USD=0.9041 €[3]
- CO_2 **price forecast (ETS market** forecast): Defined Base price (75 €/t @2025; 100 €/t @2030; 115 €/t @2035; 130 €/t @2040 and thereafter) for economic evaluation and Low and High prices for sensitivity analysis. Compared with available international organization forecasts (IEA (2019)[4], Enerdata[5], Bloomberg[6]) 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[7] (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).



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

- **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;

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[3] https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html#:~:text=Analyse%20the%20results.%20Download%20XML%20(SDMX)%20RSS%20feed%20with%20daily

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

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

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

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

  - 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.

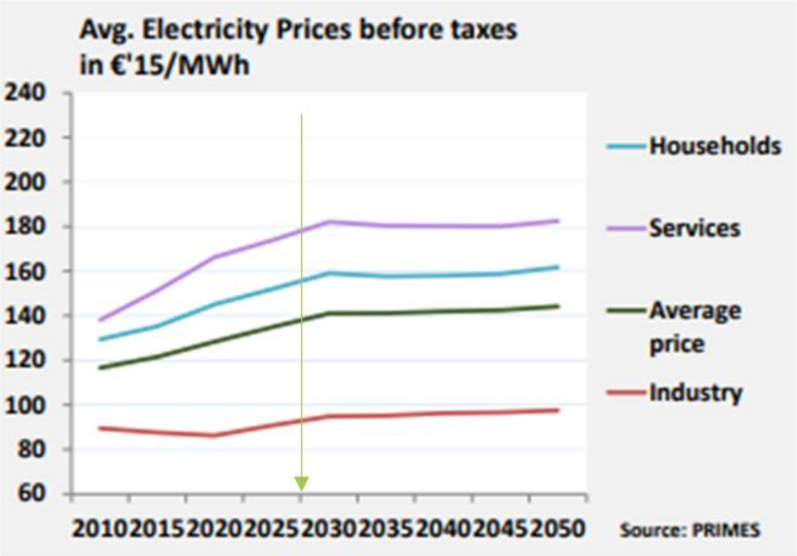

Figure 4.2 Electricity price by sector. Proposed industry profile for techno-economic evaluation (source: European Electricity Market[7])

5. Economic evaluation by regions

The development concept and its viability decision must be based on strategic information to identify and address existing risks and to commit available resources, maximising the potential for success. This strategic information was identified during a framing session phase conducted previously in the project and summarised in the D4.1 public deliverable “Methodology for alternatives Definition, Prioritisation, and Selection” (Canteli et al., 2023) for Paris Basin, Lusitanian Basin, and Ebro Basin. In D4.2 public deliverable “Conceptual scenarios definition to enable decision support” (Canteli et al., 2024), the different strategies are outlined for every region involved in the PilotSTRATEGY projects, before a comprehensive analysis of those strategies and their associated scenarios.

In the PilotSTRATEGY project frame, *scenario* refers to a technical description and planning of the CO_2 storage site life cycle valid for a specific strategy. These strategies are not only economy-driven but should also consider the different interests of potential stakeholders.

The economic evaluation of Portuguese and Spanish region is based on pre-commercial and commercial development with discounted cash-flow for the full life cycle, and considering the CO_2 at market price as income; the French case, however, is based only in pre-commercial (pilot) phase and the economic evaluation is based on required investments (no CO_2 storage accounted).

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 CO_2, as discussed and presented to local stakeholders in WP6. The CO_2 stream is almost pure CO_2 produced from SMR (steam methane reforming) operations at the plant. The plant is operating a waste-water disposal well (vertical open-hole).

5.1.1 Scenario/s selection rationale

As it was mentioned before, several scenarios are considered for the Paris Basin case (Table 5.1). This report assesses the economics of the different scenarios based upon the Capital expenditure (CAPEX) required for implementing them mainly from a transport point of view since capture and storage costs will be the same for all of them.

The foreseen scenarios consider either an intermittent injection associated with truck transport between emission and storage sites, or continuous injection either within the emission site (noted as on-site option in Table 5.1), or outside the emission site associated with short-distance pipeline transport (noted as off-site option in Table 5.1).

Table 5.1: Characteristics of the transport chain for the different scenarios for the French region

Scenario	On-site injection	Off-site injection
Pilot fast-track development at minimal cost to prove technical feasibility	Yes	Yes by truck
Prepare/develop pilot for commercial development (attract project developers): pipeline transport for off-site injection		Yes by pipeline
Minimise project footprint on local communities: on-site injection	Yes	
Foster local economy, nearby communities' development		Yes by pipeline
Show case CCS solutions and associated advantages (build world-class CCS demonstrator)	Yes	

5.1.2 Techno-economic description (activities, schedule and costs)

To assess the CAPEX of the different transport chains, the model must account for the conditioning specific to each transport chain. Prior to transport, the CO_2 need to be conditioned to meet the required pipeline or truck transport conditions (pressure, temperature and purity).

At this preliminary stage, the models are only used to estimate the CAPEX requirements to rank the different scenarios.

5.1.2.1 Pipeline Transport Chain

For pipeline transport, the conditions for large scale flow rate generally assumes liquid or supercritical conditions while for lower flow rates, gaseous conditions are acceptable but will require an additional compression unit at the storage site. Within the context of the project, such a compression unit may not be appropriate due to regulatory authorizations and possible noise-level impact. To minimize the project impacts, all the main and bulky equipment are assumed to be located on the premises of the emission

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site when possible. Thus, for an injection in a deep saline formation, the CO_2 should be in dense or liquid phase (Figure 5.1) depending on the temperature, i.e. at a pressure high enough for injection.

In Table 5.2, the CO_2 flow rate is based upon the available rate from the CO_2 source and the pipeline capacity is set to 1/3 due to the limit for the pilot injection to 0.1 Mt. The outlet pressure is set to 100 bars to be consistent with the truck transport chain (Figure 5.3). The inlet pressure is estimated from the pressure drop in the pipeline[8] using the average pressure, density and viscosity in the pipeline. This pressure drop estimate will be validated during the pipeline design. The durations for operation and construction are set to the minimum value for the cost models.

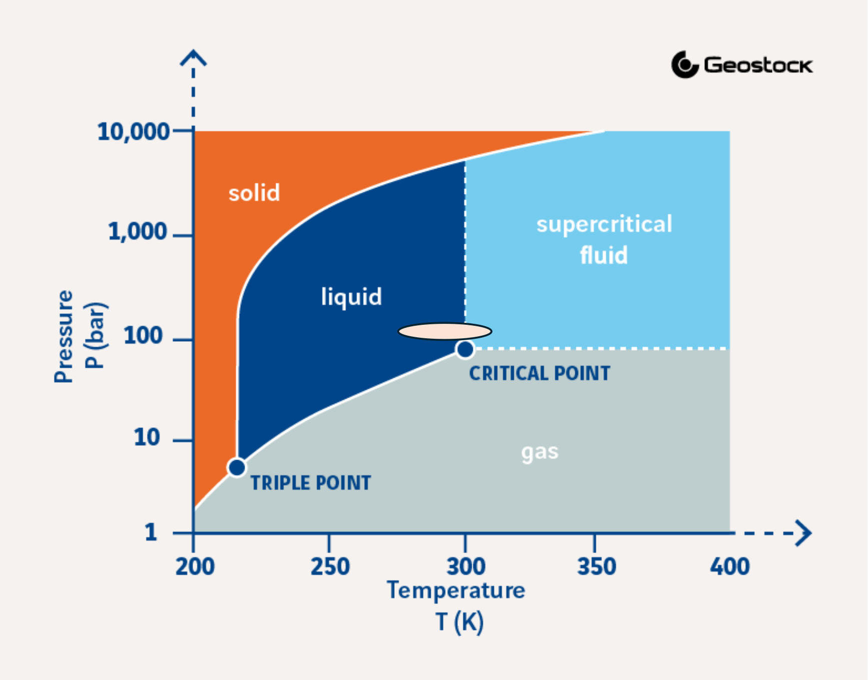

Figure 5.1 Pipeline transport conditions for injection in a saline formation

A techno-economic model for the transport of carbon dioxide (Morgan et al., 2023) estimates revenues and capital, operating and financing costs for transporting liquid/supercritical CO_2 by pipeline. It is assumed that the CO_2 delivered to the pipeline meets pipeline specifications for purity. Costs are estimated for a single point-to-point pipeline, which may have additional pumps along the pipeline to boost the pressure. The required set of parameters may be minimal as illustrated in Table 5.2:

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[8] https://www.pressure-drop.com/Online-Calculator/

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Table 5.2: Physical assumptions for pipeline cost model for the French region.

Pipeline design parameters	
Average annual mass flow of CO_2 transported (Million tonnes/yr)	0.3
Capacity factor of the pipeline (%)	33
Length of pipeline (miles/km)	1.9/3
Change in elevation from inlet to outlet of pipeline (m)	0
Inlet pressure for pipeline (psig/bar)	1510/104
Outlet pressure for pipeline (psig/bar)	1450/100
Number of booster pumps	0
Calendar year for the start of the project (yr)	2025
Duration of construction (yr)	1
Duration of operation (yr)	1

The pipeline length is obtained from the average distance between the source and the best location of the storage well as obtained from WP3 (Chassagne et al., 2024) and rounded to 3 kilometres. Figure 5.2 summarises the main pipeline parameters.

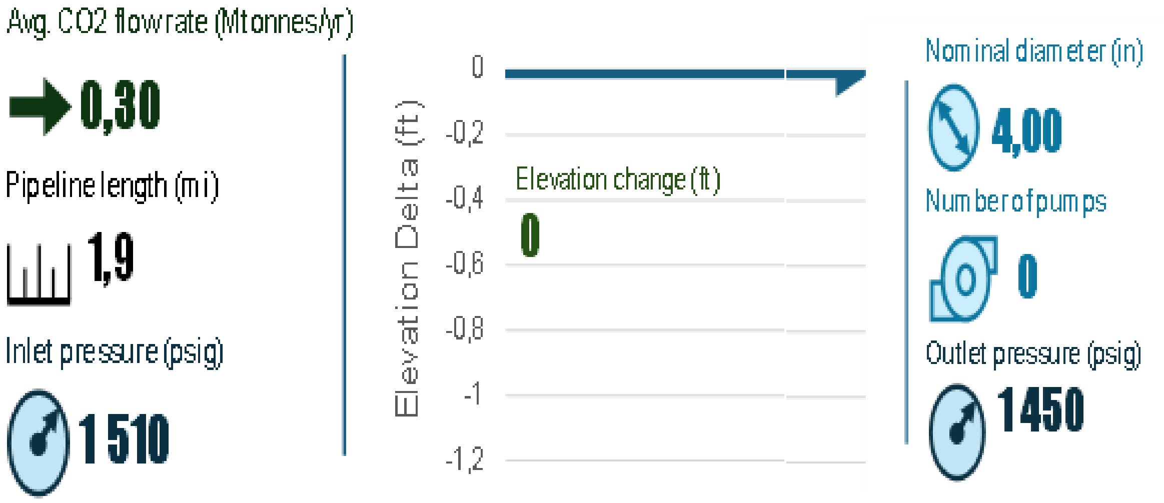

Figure 5.2 Pipeline transport chain for CO_2 pilot injection (adapted from Morgan et al., 2022)

In addition to the pipeline model, the CAPEX for compression and drying must be added as described in section 5.1.2.2.

5.1.2.2 Surface Plant model

A techno-economic analysis for typical industrial plants was performed by Hughes & Zoelle (2022). They assessed the capture cost for an ammonia plant which could be analogous to the main emission source considered in the French case. The ammonia plant uses natural gas feed stock and produces 99% pure CO_2 from the stripper at a rate of 0.486 Mtpa. The source in the French case emits 0.3 Mtpa i.e. 61.7% of the typical American plant. Consequently, the required investments are assumed to be proportional.

At this stage of the assessment, the only equipment of interest is related to CO_2 conditioning (compression and drying) as illustrated in Table 5.3.

Table 5.3: Conditioning equipment cost for the ammonia plant

Ammonia plant equipment cost	American plant ($M\$_{2021}$)	French case ($M€_{2025}$)
Inlet water knockout for compression	0.02	0.01
CO_2 compression	9.3	8.6
TEG dryer	2.9	2.6

These costs are escalated to 2025 according to the pipeline cost models:

$$€_{project\ year} = \$_{reference\ year} * (1 + exchange\ rate) * (1 + inflation\ rate) * (1 + yearly\ escalation\ rate)^{(project\ year - reference\ year)}$$

with:

Table 5.4: Assumptions for subsurface plant costs

Parameter	Value	Reference
yearly escalation rate	5.12%	US Bureau of Labor Statistics[9]
€/$ exchange rate	0.9041	September 2, 2024
Average EU27 inflation rate	2.2%	European Central Bank August 2024[10]
reference year	2021	Hughes & Zoelle (2022)
project year	2025	

5.1.2.3 Truck Transport Chain

A techno-economic model for train and truck transport of carbon dioxide (Myers et al., 2024) estimates revenues and capital, operating and financing costs for transporting liquid phase CO_2 (Figure 5.4) by truck or train in the US. The cost model accounts for the conditioning and buffer storages both at the emission and storage sites as illustrated in Figure 5.3.

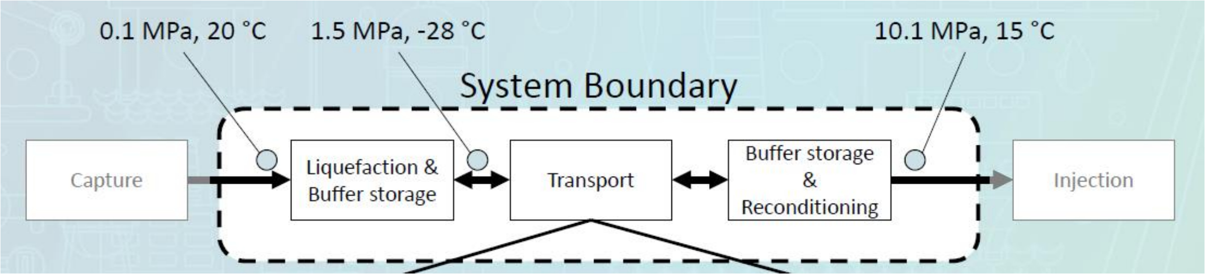

Figure 5.3 Truck transport chain for injection in a saline formation (Myers et al., 2024)

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[9] https://www.officialdata.org/us/inflation/2021?amount=1

[10] https://www.ecb.europa.eu/stats/macroeconomic_and_sectoral/hicp/more/html/data.en.html

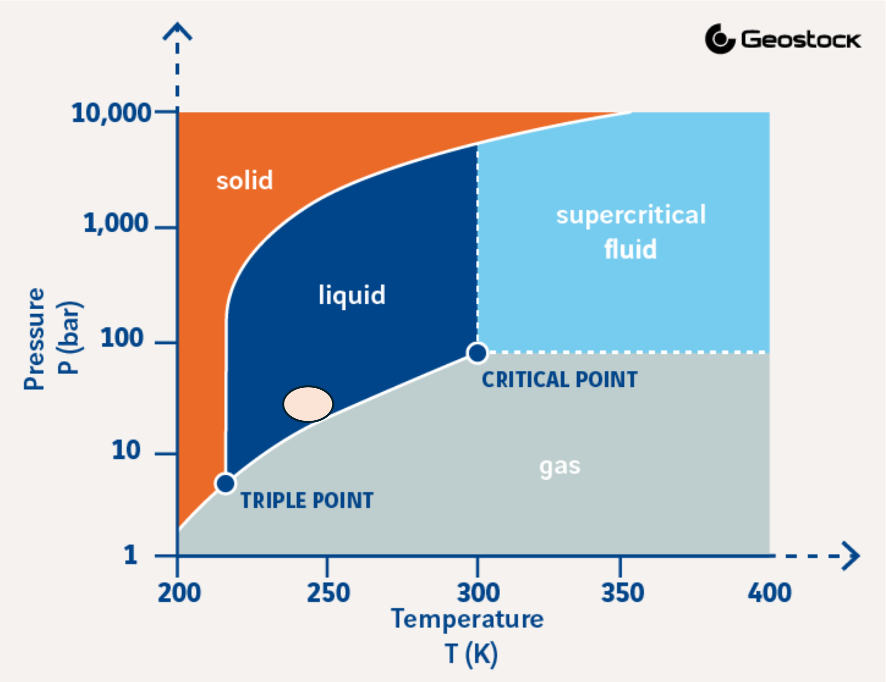

Figure 5.4 Truck transport conditions

In Table 5.5, the CO_2 flow rate is based upon the available rate from the CO_2 source and the truck capacity is set to 22 tonnes of CO_2 (default value of the model) while the two-driver mode only applies for long distance transport due to maximum regulated driving hours per day (8) which has no influence on the French case. The required numbers of trucks and trailers are computed based upon the truck round trio duration plus loading and unloading to meet the required transportation rate. The buffer storages are necessary at both plant and storage sites due to intermittency of the truck delivery (Myers et al., 2024). The mid-west plain is selected for the location as it may be analogous to the French case location (Brie plain). The minimum distance in the model is 5 miles (Table 5.5) which only influences the OPEX but does not change the required CAPEX for the case.

Table 5.5: Physical assumptions for truck cost model for the French region.

Truck design parameters	
Average annual mass flow of CO_2 transported (kt-CO_2/y)	300
Road distance (miles/km)	5/8
Location	Mid-west plain
Transport Mode	Truck
Container Type	Tanker
Water content (ppm-mol)	0
CO_2 Pressure (bar)	15
Operating Period (y)	1
Construction Period (y)	1
Construction Start Year	2025

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5.1.3 Economic results and prioritisation

Considering the pipeline and truck transport chain described above, the CAPEX of the two transport modes can be estimated as follows:

Table 5.6: Estimated CAPEX of the transport chains for the French region

Pipeline Chain	**(M€$_{2025}$)**
Pipeline	4.5
Compression	8.6
Drying	2.6
	15.7
Truck Chain	**(M€$_{2025}$)**
Liquefaction	15.3
Buffer storages	3.7
Trucks	2.4
Reconditioning eq.	4.3
	25.7

Considering the estimated transport cost (Table 5.6), any truck transport scenario would be less attractive than pipeline transport scenario even when considering renting the trucks rather than buying them (the rental cost will then be considered as operating costs). Consequently, when off-site injection is considered, the scenario should ensure compression and drying on the emission site and pipeline transport to the storage site. These scenarios have side benefits such as less bulky equipment at the storage site and lighter and limited authorization processes for surface installation at the storage site. The large equipment within the premises of the emission site should not significantly impact the environmental and administrative authorizations.

As described in Table 5.1**Erreur ! Source du renvoi introuvable.**, the transport modes of the different scenarios are function of the injection site location, either on-site or off-site. The only scenario considering truck transport for off-site injection is the “Pilot fast-track development at minimal cost to prove technical feasibility”. All the other scenarios considering off-site injection assume pipeline transport.

Consequently, there remain 2 scenarios for off-site injection and 2 for on-site injection. The latter being obviously less CAPEX intensive because no pipeline is required even though drilling length might be significantly different due to well deviation to limit interferences with disposal operations at the emission site (Figure 5.5).

The disposal well located on-site is open hole over the target formation and is used when the plant operates. Thus, interferences are expected between the brine disposal and CO_2 injection which may be detrimental to both operations. Based upon the results of D3.3 (Chassagne et al., 2024), the extension of the CO_2 plume is about 700 m around the well implying an injection point at least more than 700 m away from the disposal well. Furthermore, when considering the pressure interferences (Chassagne et al., 2024), the CO_2 injection and brine disposal should be even further away as illustrated in Figure 5.5:

- at least 3 km away from the disposal well to limit the pressure increase to 10^5 Pa (1 bar) which leads to an average deviation angle of about 56.4°.

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- at least 4 km away from the disposal well to limit the pressure increase to 0.5 10^5 Pa (0.5 bar) which leads to an average deviation angle of about 63.5°.

Such deviations exceed the standard drilling practices in the Paris Basin.

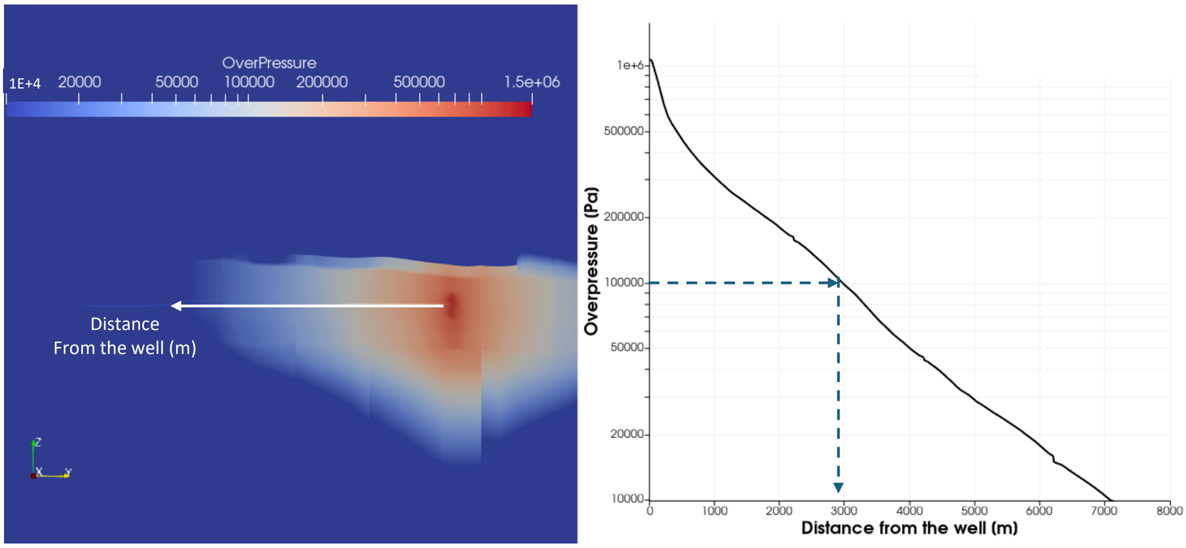

Figure 5.5 Pressure increase above the initial pressure due to CO_2 pilot injection (300 kt/y) for the base case scenario at the end of injection (4 months) (Chassagne et al., 2024)

5.1.4 Final development selection and preliminary schedule

As presented above, the required deviations of the well to limit interferences with the disposal well operations would favour **off-site injection scenarios** which will be retained for detailed dimensioning studies which includes the following designs and cost estimates:

- Compression
- Pipeline
- Injection well
- Monitoring & Verification

Considering the main technical elements (pipeline, well) and the required permitting processes and operation authorization, the preliminary planning is shown in Figure 5.6.

The preliminary schedule includes the uncertainties on the various administrative and technical tasks:

- Pipeline: preliminary studies, detailed routing, detailed studies, administrative file for permitting, administrative authorization investigations, long-lead Items, land access negotiations, construction
- Compression: detailed studies, long-lead Items, construction
- Well: detailed studies, drilling permit authorization, long-lead Items, drilling and completion

Given the various delays above, all administrative authorization would be obtained in month 37 (beginning of year 4) at the earliest. The start of CO_2 injection would be in month 62 (beginning of year 6) at the earliest while the base line monitoring might start in year 5 (Figure 5.6).

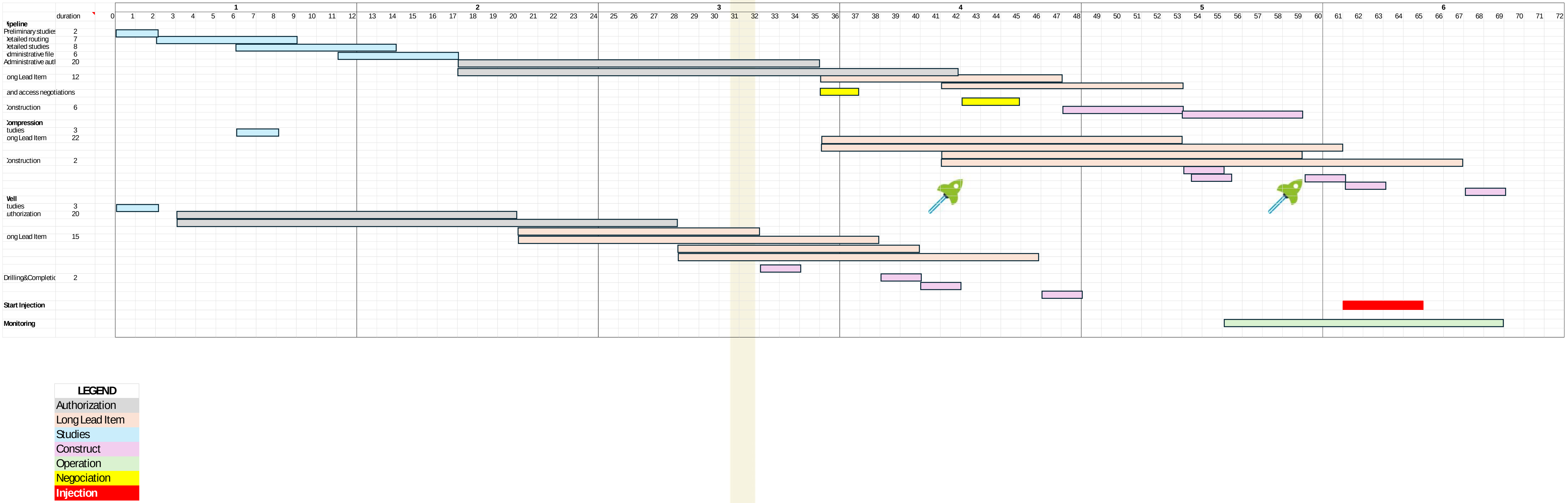

Figure 5.6 Foreseen schedule for the CO_2 pilot injection considering the technical and administrative durations and uncertainties

5.2 Lusitanian Basin (Portugal)

5.2.1 Scenario/s selection rationale

The baseline case for the Lusitanian Basin CCS project, considered from the Framing Sessions (Canteli et al., 2023), comprehends two injection phases: Phase I – a **pilot-scale injection** of up to 100 kt CO_2 for 5 years – followed by Phase II – **commercial upscaling** injection of up to 0.5 Mt/year during a 30 year timespan, as discussed during workshops and follow-up meetings and as presented to regional stakeholder committee meetings. The foreseen scenarios consider 1) an intermittent injection associated with train transport between local CO_2 point sources and storage sites and 2) continuous injection from the Figueira da Foz port with offshore pipeline transport (23 km).

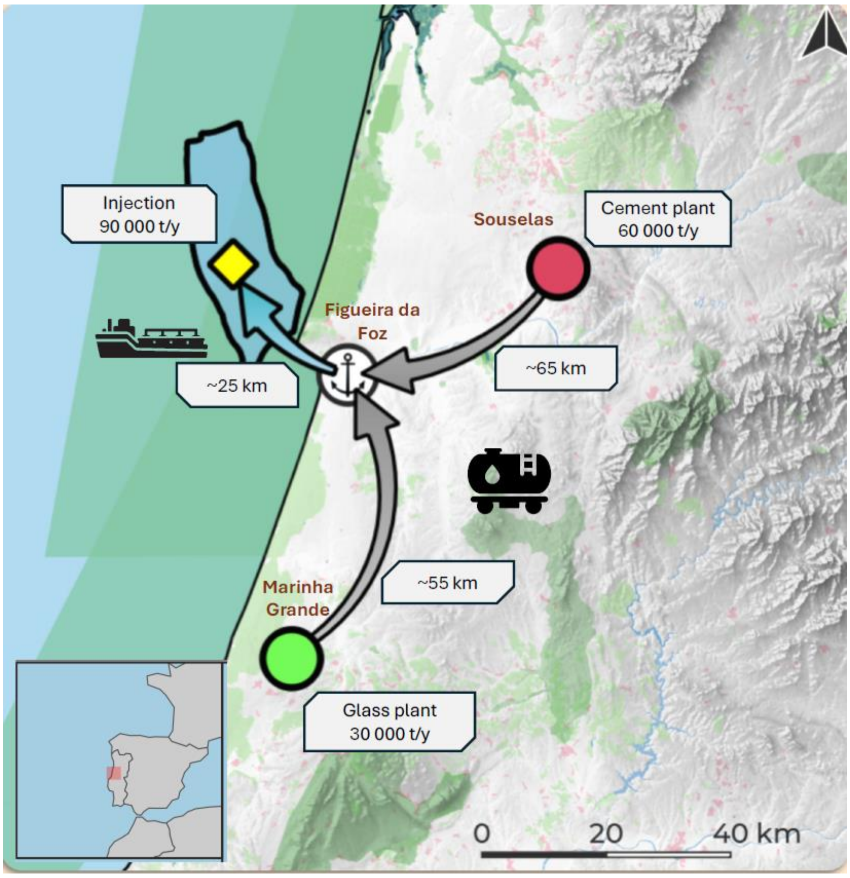

Figure 5.7 Location of the main local CO_2 emitters, previously identified in StrategyCCUS (Mesquita et al., 2024)

For the pilot phase, CO_2 sources are assumed to be from the closer points (cement/lime, glass, and paper and pulp industries), 50 to 80 km from the storage site, as identified in StrategyCCUS [11] (Figure 5.7). StrategyCCUS also considered the possibility of a limited amount of 60-90 kt CO_2 per year and CO_2 transport by railway & ship as the best option, given the flexibility, cost efficiency, and the relatively low infrastructural impact. Avoiding pipeline transport in the pilot phase would also dramatically decrease CAPEX costs, motivated by the subsurface uncertainties to be de-risked and the regulatory gaps still associated with this option. Shipping transport to the storage site would be

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[11] STRATEGY CCUS (H2020-LC-SC3-2018-2019-2020/H2020-LC-SC3-2018-NZE-CC) https://strategyccus.brgm.fr/

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enough to ensure continuous injection and avoid the need for permanent infrastructure in the early project stages.

5.2.2 Techno-economic description (actions, schedule and costs)

As described, development scenarios resulting from the Framing Sessions were framed in two stages or phases: the pilot phase (or pre-commercial) and the commercial phase. The costs of both phases are here detailed, considering the pilot phase as an exploratory phase that will help to decide about the commercial phase's viability. In D4.2 (Canteli et al., 2024), several scenarios were considered for the Lusitanian Basin:

1) Minimum cost.
2) Social engagement, awareness, local development.
3) Regulatory gaps understanding and research.
4) Schedule and accelerating the pilot development.
5) Enhance the commercial development.
6) Limit HSE risk and reduce territorial impacts.

These scenarios were used as the basis for assessing the development options of the project. Given the magnitude and impact of such an industrial project set in mixed offshore and onshore, the team decided to narrow the development criteria down to subsurface and infrastructural critical components. Subsurface characterisation and its related uncertainties need to be properly managed in order to tackle higher HSE demands as well as reduce costs related to facilities.

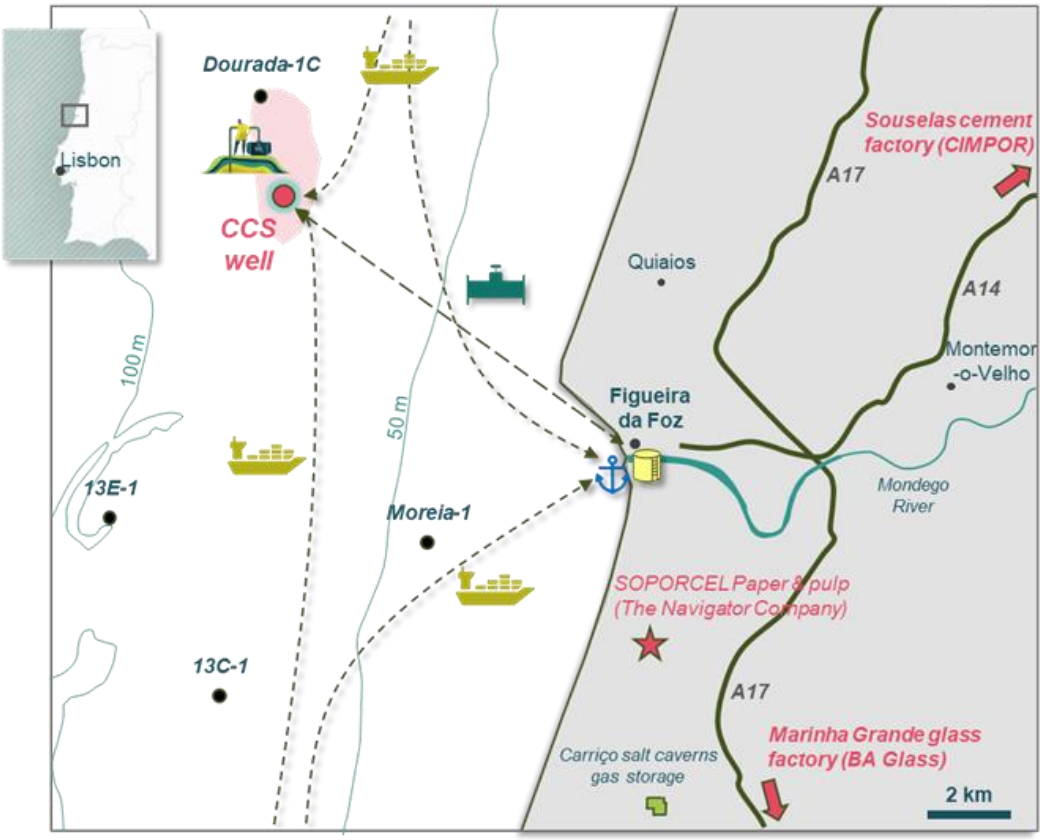

Figure 5.8 Main offshore transport options considered from the Figueira da Foz port to the storage site.

The development options here considered take into account two critical CO_2 transport options, considered for the pilot (fast-track development at minimal cost to prove technical feasibility) and commercial phases (full-scale CO_2 storage): 1) Train to Figueira da Foz port & shipping to storage site, and 2) train to Figueira da Foz & pipeline to/from Figueira da Foz port.

5.2.2.1 Transport option

The project leverages the proximity of railway infrastructure at both the capture and port facilities, making railway transport the most practical and cost-effective solution for delivering CO_2 to Figueira da Foz. The CO_2 would be transported in a liquified state at a pressure of 6.6 bar and a temperature of -50°C. Each train has a capacity of 4,000 tonnes, completing a round trip in approximately 12 hours, which includes time for loading and unloading. Over the course of three years, the total CO_2 transported to Figueira da Foz is projected to reach 270 kt. As it is mentioned later, due to legal limitation to 100 kt for a pilot, the project will require a license extension after the first year of operations to proceed as planned.

To enhance operational efficiency, the transport system is being carefully aligned with the conditions required at the Figueira da Foz port and the offshore injection well. This alignment would eliminate the need for intermediate storage or reconditioning at the port, reducing both costs and complexity. Train waggons may serve as temporary storage units or be directly unloaded onto ships, ensuring that CO_2 is maintained at its original pressure and temperature throughout the transportation process.

5.2.2.2 Injection Pilot Phase

The injection pilot phase is designed to achieve three primary objectives: to characterise the offshore reservoir, test the CO_2 injection conditions, and assess the quality of the caprock to ensure secure long-term storage. The pilot is designed to inject CO_2 at a rate of 90 kt per year, with a total injection volume of 270 kt over three years.

A significant regulatory challenge for the pilot phase is the limitation imposed by Portuguese law DL 60/2012, which restricts CCS projects to a total injection of 100 kt without additional licensing. This means that the project will require a license extension after the first year of operations to proceed as planned (**Erreur ! Source du renvoi introuvable.**).

5.2.2.3 Transport from Figueira da Foz to the Injection Well

The transport infrastructure between Figueira da Foz and the offshore injection well must balance flexibility, cost, and adaptability to project uncertainties. Flexibility is crucial to accommodate variations in CO_2 injection rates, especially during the pilot phase. Additionally, avoiding permanent infrastructure investments minimises financial risk, particularly in the event of poor reservoir performance or unexpected issues with caprock integrity.

5.2.2.4 Pipeline Transport

Transporting CO_2 via pipeline offers a technically feasible option, but it faces several drawbacks during the pilot phase. A pipeline designed to accommodate long-term mass flow rates – up to 4.73 Mt per year by 2050 – would need an 8- or 10-inch diameter. However, such a pipeline would require significant investments in conditioning facilities at Figueira da Foz, even during the low-volume pilot phase. This results in disproportionately high CAPEX for a project handling only 270 kt of CO_2.

In addition, maintaining the required pressure and temperature conditions in a large-diameter pipeline for low flow rates introduces operational uncertainties. For these reasons, a pipeline is better

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suited for large-scale, long-term projects rather than pilot-scale operations, and that is why it is only being considered for phase II (commercial project).

5.2.2.5 Ship Transport

Transporting CO_2 by ship presents a more flexible and cost-effective solution for the pilot phase. Ships can accommodate variable flow rates and avoid the need for permanent infrastructure at the port. The proposed ships would have a capacity of 4,000 tonnes, matching the train waggons' capacity, and could complete a round trip in approximately 80 hours.

Ship-based transport allows CO_2 to be maintained in its liquified state at the same pressure and temperature conditions used during train transport, thus eliminating the need for reconditioning at Figueira da Foz. Train waggons can be directly loaded onto ships, further simplifying operations and removing the need for temporary storage at the port. Once at the offshore site, the ship can either inject CO_2 directly into the well or transfer it to a floating platform equipped with conditioning facilities.

However, one challenge associated with ship transport is the high capital cost of acquiring a dedicated vessel. For the pilot phase, renting or retrofitting an existing ship is recommended to reduce upfront costs while maintaining operational flexibility.

The transport system should be designed with modularity in mind, allowing a seamless transition from shipping transport to pipeline infrastructure as injection rates increase and the CCS site scales up to meet long-term goals.

5.2.3 Economic results and prioritization

To assess the CAPEX of the different transport chains, estimations only considered transport from the local emitters to the Figueira da Foz port. Details on the capture and conditioning of CO_2 at the sources were not considered in this project, although it was assumed the highest degree of CO_2 purity and pressure before being transported by train.

The techno-economic assumptions from the French case (Myers et al., 2024) were used as a reference to define the operating and financing costs for the onshore transport of liquid CO_2 (Table 5.7).

Table 5.7 Physical assumptions for train cost model for the Portuguese region.

Scope	Cement plant	Glass plant
Average annual mass flow of CO_2 transported (kt-CO_2/y)	30,000	60,000
Road distance (km)	65	55
Location	Souselas	Marinha Grande
Transport Mode	Railway	Railway
Container Type	Tanker/Waggon	Tanker/Waggon
Water content (ppm-mol)	0	0
CO_2 Pressure (bar)	6.6	6.6
CO_2 Temperature (ºC)	-50	-50

Considering the shipping & pipeline transport chain described above, the CAPEX of the two transport modes and general infrastructure can be estimated as follows:

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Table 5.8 Estimated CAPEX of the transport chains for the Portuguese region (TBD – to be defined; Railway transport cost estimated from StrategyCCUS project)

Scope	Phase I – Pilot		Phase II – Commercial	
	Detail	Cost (M€)	Detail	Cost (M€)
Permitting	Guarantee transport licences (train + shipping)	0.2	Guarantee transport licence (train + pipeline)	0.2
Infrastructure	Liquified CO_2 tanker	TBD	Liquified CO_2 tanker	TBD
	Figueira da Foz port offloading/loading facilities	TBD	Figueira da Foz port offloading/loading facilities – high pressure shipping, requiring boundary station (post-metering at 70 bar) and temporary pressurized storage	2.5
Railway (estimated in 2030)	Railway from Souselas and Marinha Grande industrial sources	10-20€/tonCO_2	Railway from Souselas and Marinha Grande industrial sources	10-20€/tonCO_2
Pipeline	Offshore pipeline (23 km, 8´´)	N/A	Offshore pipeline (23 km, 8´´)	20
Injection facility	Injection platform (no heavy subsea infrastructure)	TBD	Manifold & wellhead (incl. block valve module)	TBD

Despite the uncertainties on the feasibility and costs of the shipping option, this combination with railway transport appears more attractive for Phase I, when compared to railway & pipeline transport. This flexible approach offers additional advantages, such as reducing the need for bulky equipment at the storage site and streamlining authorisation processes for surface installations while minimising the environmental and administrative challenges associated with securing permits.

As detailed in

Table 5.8, the choice of transport mode depends on the project phases. Among the scenarios considered, railway transport and shipping are proposed only in the Phase I (fast-track development at minimal cost to prove technical feasibility). The commercial injection (Phase II) scenario prioritises offshore pipeline transport due to its operational and logistical advantages.

5.2.4 Final development selection

As presented above, the required permits, well drilling & completion, transportation, and facilities construction favour a multiphased project dimensioning, which would also include MMV planning and execution.

Considering the main technical elements (e.g., train, shipping, pipeline, well) and the required permitting processes and authority approvals, the preliminary planning is shown in Figure 5.9.

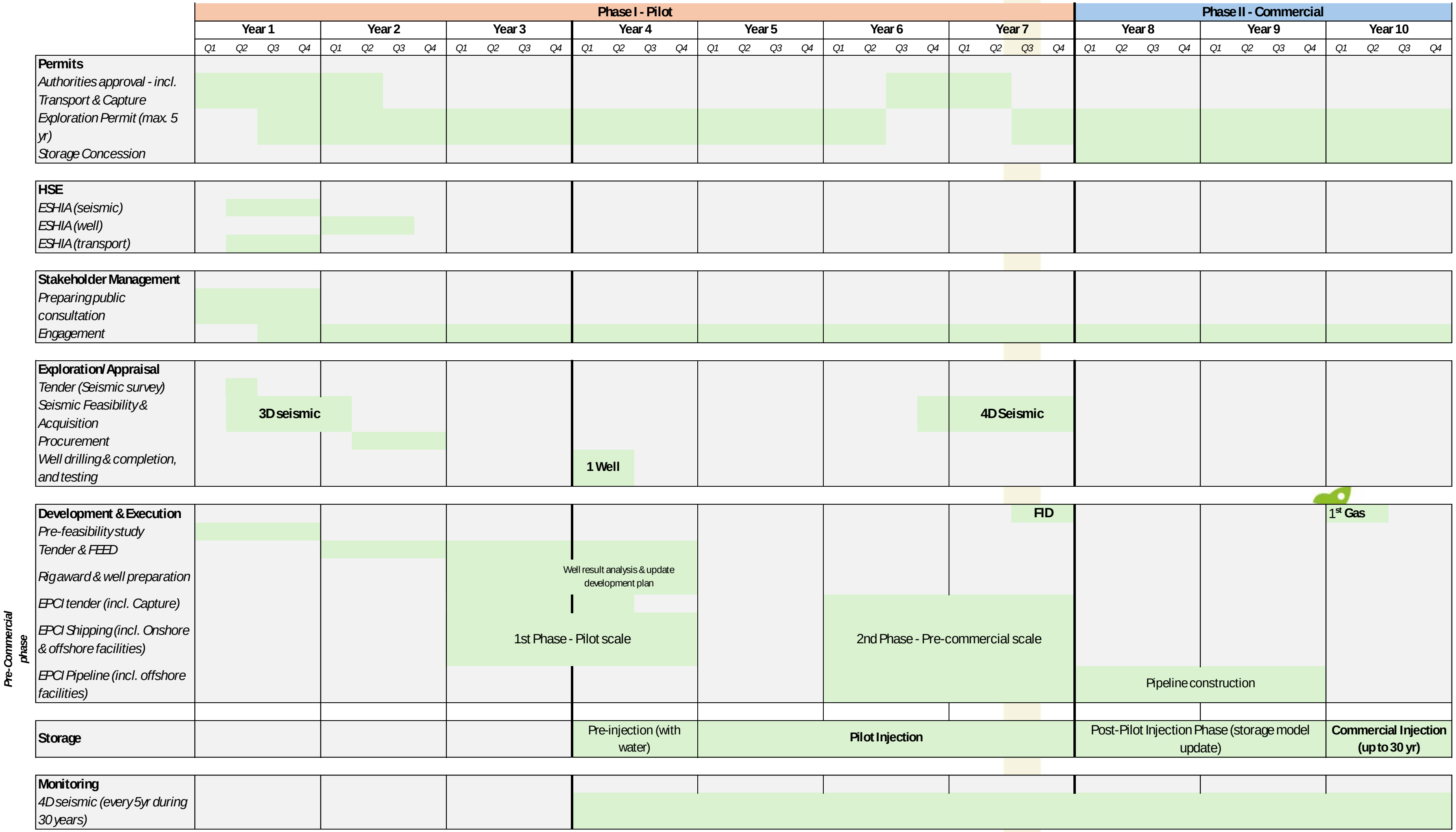
This preliminary schedule includes the uncertainties on the various administrative and technical tasks regarding, for the pilot/pre-commercial and commercial phases:

- Permitting, including authorities' approval
- HSE feasibility studies (ESHIA)

- Tender for seismic acquisition
- Tender for well drilling & completion and testing
- Tender for onshore & offshore transport facilities permitting, construction, including train adaptation, long-lead items (e.g. cargo), shipping and pipeline

Given the expected delays, particularly concerning authority approvals and securing CO_2 transportation facilities adaptation & construction, it is foreseen that pilot injection starts by year 5, after seismic acquisition & processing (year 1 – year 2) and well drilling (year 4).

The start of pilot CO2 injection would be in year 5, followed by 4D seismic acquisition by year 6/7, which would allow us to understand the plume evolution and de-risk the main subsurface uncertainties already identified. This would allow FID of the commercial upscaling by the end of year 7, in order to start developing the Phase II injection with the pipeline development and commercial injection only by year 10 (Figure 5.9).



	Phase I - Pilot																												Phase II - Commercial											
	Year 1				Year 2				Year 3				Year 4				Year 5				Year 6				Year 7				Year 8				Year 9				Year 10			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Permits																																								
Authorities approval - incl. Transport & Capture	🟩	🟩	🟩	🟩	🟩	🟩																	🟩	🟩	🟩	🟩														
Exploration Permit (max. 5 yr)			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩					🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Storage Concession																																								
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ESHIA (seismic)		🟩	🟩	🟩																																				
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ESHIA (transport)		🟩	🟩	🟩																																				
Stakeholder Management																																								
Preparing public consultation	🟩	🟩	🟩	🟩																																				
Engagement			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Exploration/ Appraisal																																								
Tender (Seismic survey)		🟩																																						
Seismic Feasibility & Acquisition		🟩 **3D seismic**	🟩	🟩	🟩																			🟩	🟩 **4D Seismic**	🟩	🟩	🟩												
Procurement						🟩	🟩	🟩																																
Well drilling & completion, and testing													🟩 **1 Well**	🟩																										
Development & Execution																											🟩 **FID**	🟩									🟩 **1st Gas**	🟩		
Pre-feasibility study	🟩	🟩	🟩	🟩																																				
Tender & FEED					🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩																								
Rig award & well preparation									🟩	🟩	🟩	🟩	🟩 Well result analysis & update development plan	🟩	🟩	🟩																								
EPCI tender (incl. Capture)									🟩	🟩	🟩	🟩	🟩	🟩							🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩												
EPCI Shipping (incl. Onshore & offshore facilities)									🟩	🟩	🟩	🟩	🟩 1st Phase - Pilot scale	🟩	🟩	🟩					🟩	🟩	🟩	🟩	🟩 2nd Phase - Pre-commercial scale	🟩	🟩	🟩												
EPCI Pipeline (incl. offshore facilities)																					🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 Pipeline construction	🟩	🟩	🟩	🟩	🟩	🟩	🟩				
Storage													🟩 Pre-injection (with water)	🟩	🟩	🟩	🟩 **Pilot Injection**	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 Post-Pilot Injection Phase (storage model update)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩 **Commercial Injection (up to 30 yr)**	🟩	🟩	🟩
Monitoring																																								
4D seismic (every 5yr during 30 years)													🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Figure 5.9 preliminary planning of the Portuguese region.

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5.3 Ebro Basin (Spain)

5.3.1 Scenario/s selection rationale

Ebro basin scenarios are based on a pre-commercial phase (pilot scale) and a commercial phase with full life cycle evaluation under the common economic frame and approach described earlier. The evaluation includes the storage site operation; that is, neither capture nor transport is included (Figure 5.10). It is assumed CO_2 stream impurities are compatible with the Lopín storage site and there are no limitations due to CO_2 quality. Selected scenarios have been described, economically evaluated for the full life cycle, and economic parameters compared in order to select the optimum option.

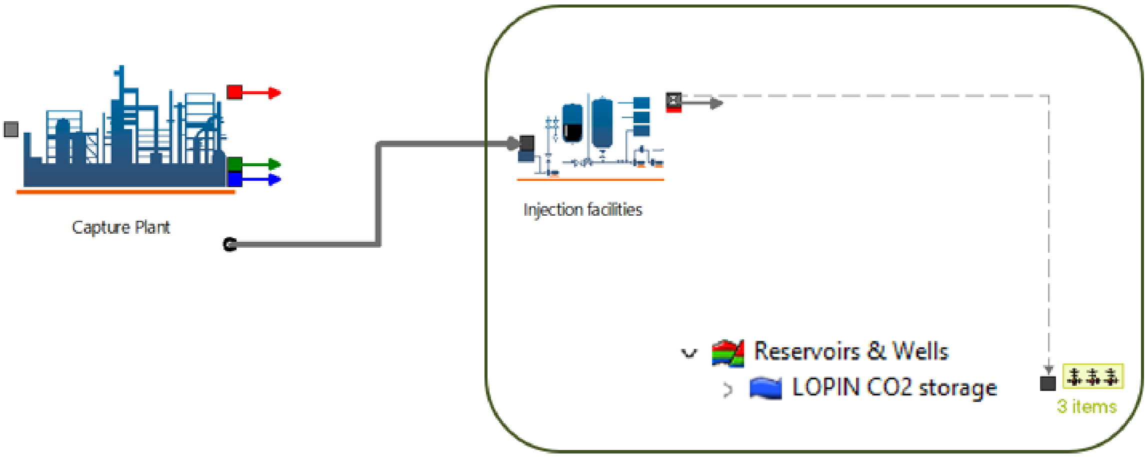

Figure 5.10 Ebro Basin scenario: only storage site operations are considered in the economic evaluation.

The Ebro basin 5 scenarios described in the D4.2 deliverable “Conceptual scenarios definition to enable decision support” (Canteli et al., 2024) were based on 5 different strategies or main goals:

1) Minimum investment
2) Social engagement and local development
3) Regulatory gaps identification for best practices and recommendations
4) Enhance commercial development (potential commercial development after pilot)
5) Minimum uncertainty on HSE risks (well-known practices)

For an economic evaluation purpose, it was agreed that those objectives could be combined in 3 scenarios, simplifying the evaluation and their interpretation. The following three scenarios have been designed for a secure storage site:

- **Minimum investment**: proposed development based on minimising initial investment and optimized operational costs (OPEX).
- **First-of-its-kind**: following current proposals for ongoing developments, which main priority is to build social thrust, validate best practices, and dimension MMV activities for an exhaustive control.
- **Green development**: similar to the previous one but ensuring a green energy supply and optimising energy consumption.

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Defined scenarios are valid for any of the following cases:

1) Permit for a pilot with a research goal, a limitation of 100 kt total CO_2 injected, and granting a commercial exploitation permit after it (under Mining Law -pilot- and CO_2 storage law)[12].
2) Permit for a commercial storage site with an initial exploration phase (injection tests limited to those 100 kt) and an exploitation phase (under CO_2 storage law[12]).

The work carried out on the dynamic modelling (WP3, D3.3 Report on optimisation – Injection strategy and storage capacity, Chassagne, 2024) has been focused on the base case scenario (defined in WP2 and assuming compartmentalisation) for a pilot case (limited to 100 kt) with a maximum storage capacity of CO_2 safely injected over a period of 30 years at optimal injection rates for a vertical well design of 2.14 million tonnes (P50 and injection rate of approx. 70 kt/yr) or 2 vertical wells with a 4.2 million tonnes estimated capacity with the same injection rates. On the other hand, the most optimistic case, with no compartmentalisation, has an estimated capacity of 23 Mt, and it was also considered with 1 or 2 wells and a maximum injection rate of 0.5 Mt/yr per well to limit the maximum pressure front (verified by a one-dimension risk evaluation model, WP5).

These 3 cases have been evaluated for the 3 scenarios using the commercial software PetroVR for CO_2 storage (Quorum software).

Cases: Estimated capacity	**2,1 Mt**	**4,2 Mt**	**23 Mt**
Injector wells (n)	1	2	1 or 2
Injection rate per well	0.07 Mt/year	0.07 Mt/year	0.5 Mt/year
Storage years	30	30	Reach max capacity

Table 5.9 Cases defined based on estimated capacity.

5.3.2 Techno-economic description (actions, schedule and costs)

The main differences between scenarios come from the exploration planning, number of injector wells, and MMV plan. The operativity of each scenario is limited by the estimated capacity and injection rate.

Although some costs are provided as a range, the economic evaluation was deterministic and based on P50 value.

5.3.2.1 Minimum investment scenario

The minimum investment scenario looks for minimising investment and optimize operative costs but always ensuring a safe storage site.

The exploration phase includes (Figure 5.11):

- Permit-granting process (12 months)
- G&G activities (12 months)
- Exploration well design (12 months), assuming G&G positive results.
- Reused exploration well followed by completion (1 injector well)
- Initial injection test of 0.03 Mt/yr for 3 years; 0.5 Mt/yr thereafter if 23Mt-case (and 0,07 in others)

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[12] "Ley 22/1973, de 21 de julio, de Minas." https://www.boe.es/buscar/act.php?id=BOE-A-1973-1018; "Ley 40/2010, de 29 de diciembre, de almacenamiento geológico de dióxido de carbono." https://boe.es/buscar/act.php?id=BOE-A-2010-20049

- Injection facilities design and building.
- MMV: Monitoring well (out of area of plume expansion) and fibre optic in the injector.
- Abandon when maximum capacity is reached.

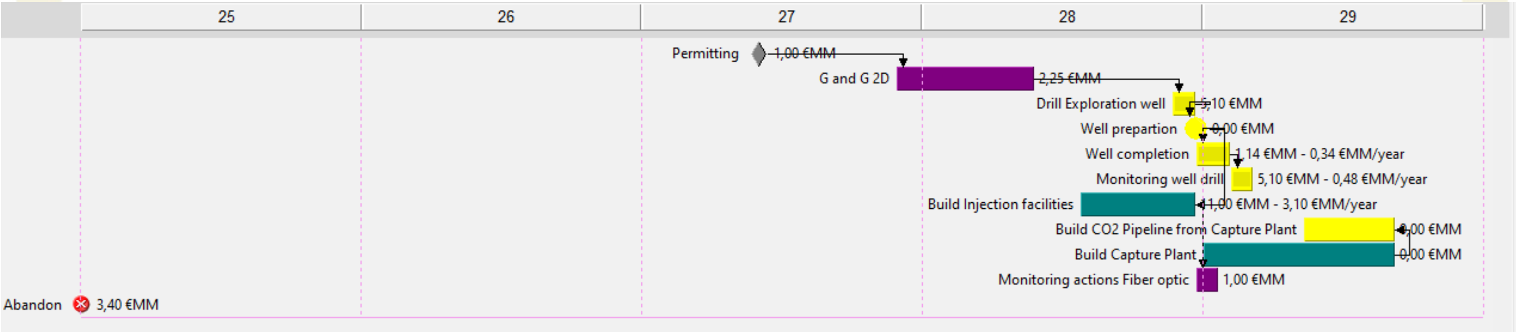
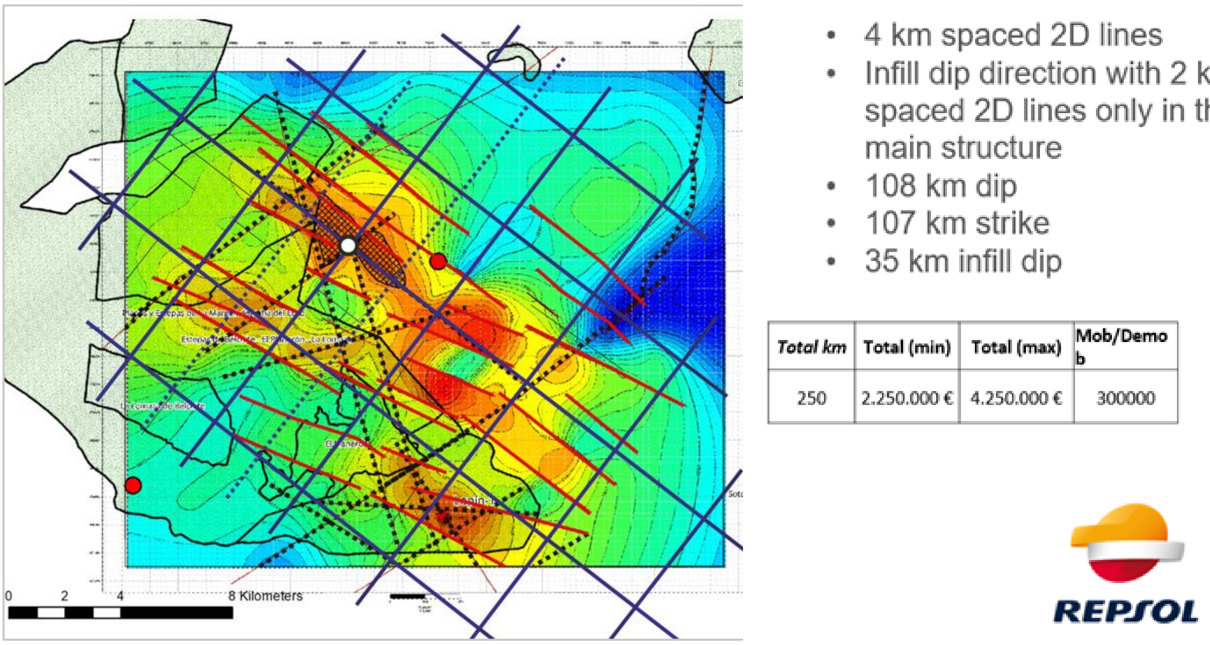


Figure 5.11 Minimum costs scenario activities schedule starting in 2025 works for permitting

Seismic survey is based on 2D surveys in the area covering the main structure and completing existing seismic lines (

Figure 5.12).



- 4 km spaced 2D lines
- Infill dip direction with 2 km spaced 2D lines only in the main structure
- 108 km dip
- 107 km strike
- 35 km infill dip

Total km	Total (min)	Total (max)	Mob/Demob
250	2.250.000 €	4.250.000 €	300000

Figure 5.12 2D acquisition design and costs estimation for minimum costs scenario

The cost of drilling an exploration well and its testing is 5.1 M€, assuming 1600 m depth, a 150-200 tonnes rig, and 30-days operation, and 1.8 M€ CO_2 for the completion, thereafter, based on the current cost of a Viura-2 well in La Rioja (2024, Spain).

Finally, cost estimation and conditions for the reception and injection facilities have been estimated assuming an onshore pipeline in dense phase to the site at 30 ºC and 85 bars, reception tanks, transport, and pumping to the wellhead with injection at 41 ºC and 174 bars, with an estimated cost of 11.2 M€ investment and 2.5 M€/year OPEX (Figure 5.13).

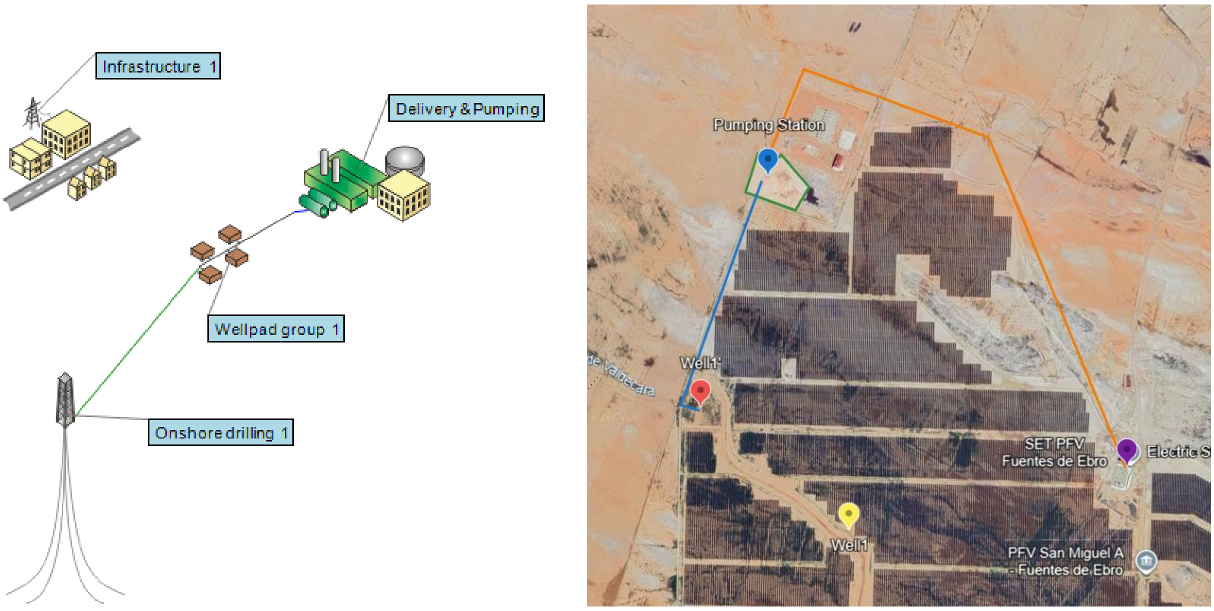


Figure 5.13 Schematic reception and injection facilities design (1 well)

5.3.2.2 First of its kind scenario

Following current proposals for ongoing developments, this scenario has as its main priorities building trust and confidence in the society, validating best practices, and fitting MMV activities for exhaustive control.

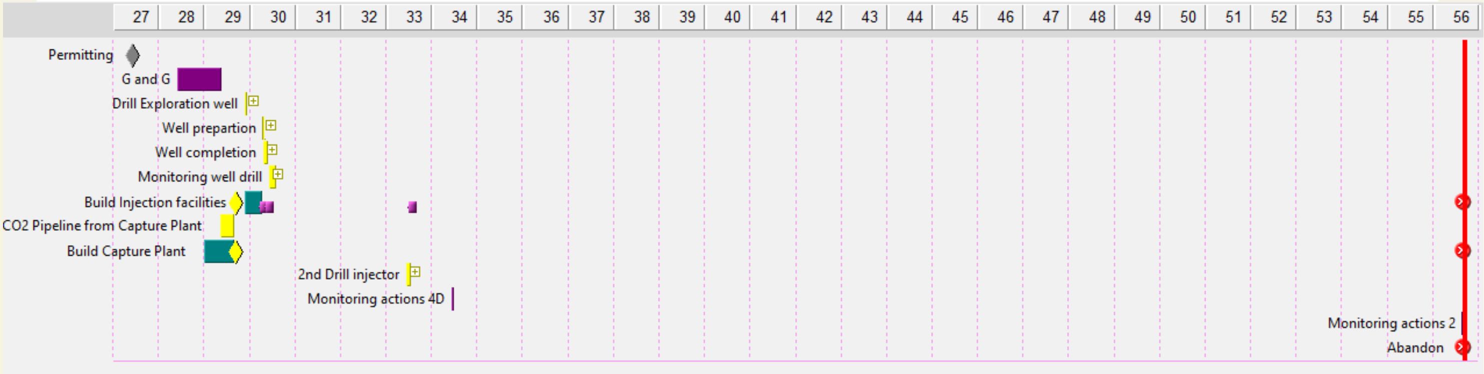


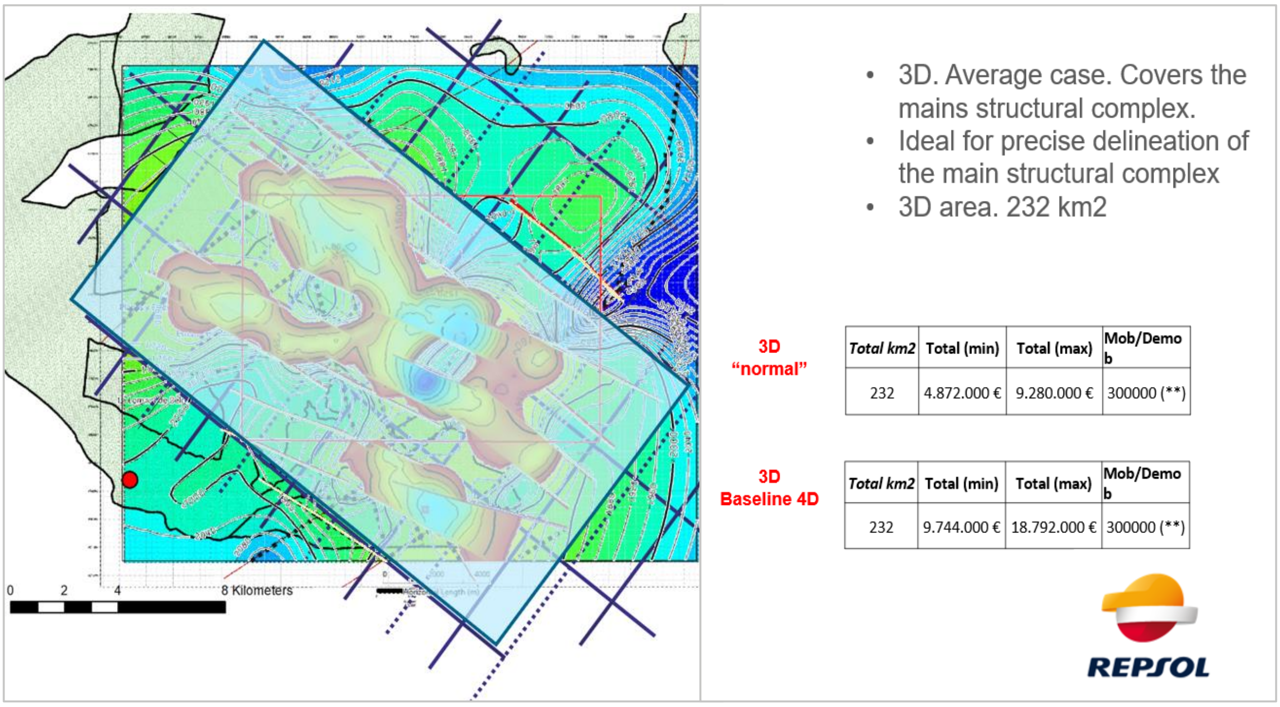
Figure 5.14 First of its kind scenario activities schedule and results for 23 Mt capacity case.

The exploration phase includes (Figure 5.14):

- Permit-granting process (12 months)
- G&G activities (12 months)
- Exploration well design (12 months) assuming G&G positive results.
- Reused exploration well followed by a completion (1 injector well) and a new well injector (3 years later)
- Injection test initial of 0.03 Mt/yr for 1 year; 0.5 Mt/yr thereafter for each well if 23 Mt-case (and 0.07 Mt/year in other cases).

- Injection facilities design and building on time.
- MMV: 2 monitoring wells (out of the area of plume expansion), fibre optic in injector, and 4D surveys every 6 years.
- Abandon when maximum capacity is reached.

Geophysical surveys are based on 3D surveys in the area covering the main structure and supplementing existing seismic lines. Seismic survey is repeated every 6 years as part of the monitoring strategy (Figure 5.15).



- 3D. Average case. Covers the mains structural complex.
- Ideal for precise delineation of the main structural complex
- 3D area. 232 km2

3D “normal”

Total km2	Total (min)	Total (max)	Mob/Demob
232	4.872.000 €	9.280.000 €	300000 (**)

3D Baseline 4D

Total km2	Total (min)	Total (max)	Mob/Demob
232	9.744.000 €	18.792.000 €	300000 (**)

Figure 5.15 3D acquisition design and costs estimation for first of its kind scenario

The cost of the exploration well and test is 5.1 M€, assuming 1600 m depth, a 150-200 tonnes rig, and 30 operation days. It is assumed there are 1.5 years between exploration well results and running the final completion with a new and lighter rig for completion of 2.8 M€ based on the current cost of a drilled well in La Rioja (Spain). New injector well cost of 6.9 M€.

Finally, cost estimation and conditions for the reception installation and injection facility have been estimated assuming an onshore pipeline in dense phase to the site at 30 ºC and 85 bars, reception tanks, transport, and pumping to the wellhead with injection at 41 ºC and 174 bars for each well, with an estimated cost of 27 M€ investment and 4.85 M€/year OPEX.

	Action Type	Perform Task	Start Condition	Date	Link Type	Linked Job	When	CapEx €MM	OpEx €MM/year
Permitting	Milestone	true	Date	01/06/2027	start			0,80	-
G and G	GandG	true	Link	31/05/2028	start	Permitting	finishes	6,25	-
Drill Exploration well	Drilling	true	Link	22/11/2029	start	G and G	finishes	5,15	0,00
Well prepartion	Drilling	true	Link	21/04/2030	start	Drill Exploration well	finishes	0,00	0,00
Well completion	Completion	true	Link	21/04/2030	start	Well prepartion	finishes	1,14	0,00
Monitoring well drill	Drilling	true	Link	05/06/2030	start	Well completion	finishes	10,70	0,95
Build Injection facilities	Facility	true	Link	22/11/2029	finish	Well prepartion	finishes	27,00	4,85
Build CO2 Pipeline from Capture Plant	Pipeline	true	Link	11/05/2029	finish	Build Capture Plant	finishes	0,00	0,00
Build Capture Plant	Facility	true	Date	01/01/2029	start			0,00	0,00
2nd Drill injector	Drilling	true	Link	02/12/2030	start	Well completion	finishes	6,90	0,00
Monitoring actions 4D	GandG	true	Link	15/01/2036	start	2nd Drill injector	finishes	6,00	-
Monitoring actions 2	GandG	true	Link	12/02/2041	start	Monitoring actions 4D	finishes	6,00	-
Abandon	Abandonment	true	Measure	01/01/2025	start			7,50	-

Figure 5.16 Summary of estimated costs for First of its kind scenario

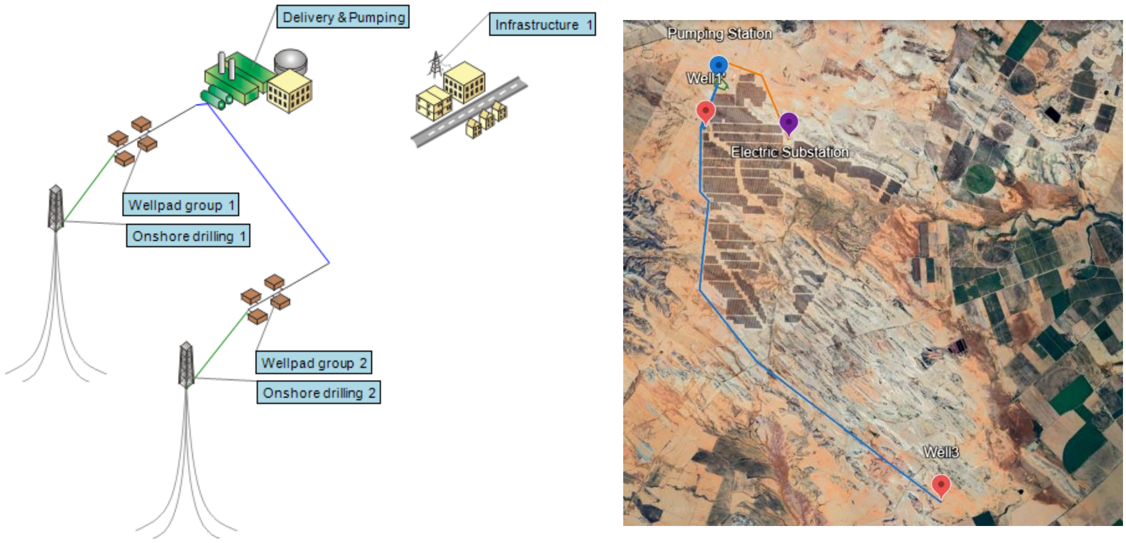


Figure 5.17 Schematic reception and injection facilities design (2 wells) for First of its kind scenarios.

5.3.2.3 Green development scenario

Green scenario evaluates the impact of green energy sources and energy optimisation. In this case, energy from the network is substituted by solar panels that are built next to the facilities. Total electrical power of 6 MW (5.4 M€).

The exploration phase includes:

- Permit-granting process (12 months)

- G&G activities (12 months)
- Exploration well design (12 months), assuming G&G positive results.
- Reused exploration well followed by completion (1 injector well) and a new well injector (3 years later)
- Injection test initial of 0.03 Mt/yr during 1 year; 0.5 Mt/yr thereafter for each well.
- Injection facilities design and building on time.
- MMV: Monitoring well (out of the area of plume expansion), fibre optic in injector, and 4D surveys after 6 years of 2nd injector well.
- Abandon when maximum capacity is reached.

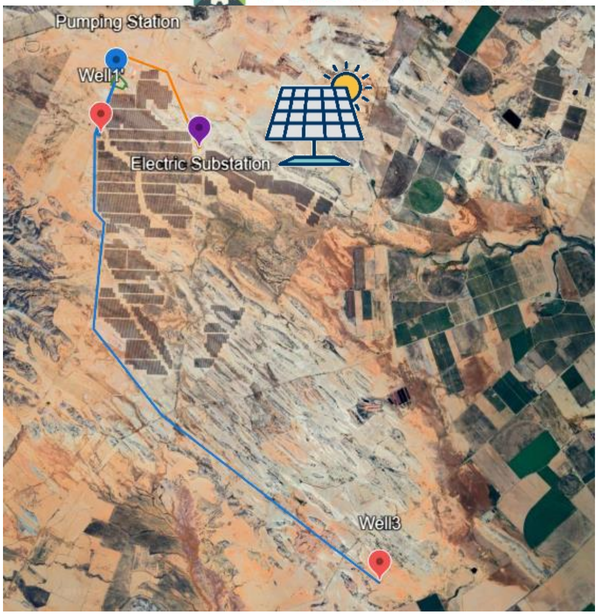


Figure 5.18 Schematic reception and injection facilities design (2 wells) for Green development.

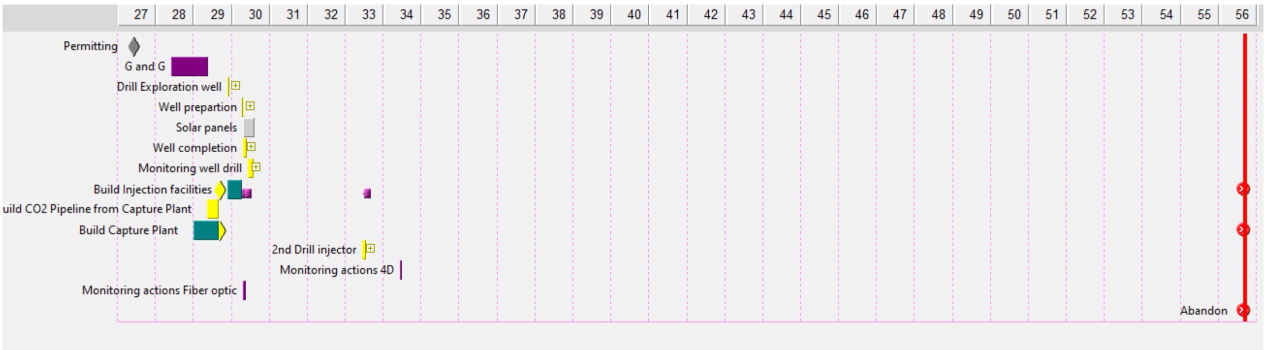


Figure 5.19 Green Development scenario activities schedule for 23 Mt case.

Geophysical surveys are based on 3D surveys in the area covering the main structure and supplementing existing seismic lines, as in the previous scenario. Again, like in the previous scenario, the cost of the exploration well and its test is 5.1 M€, assuming 1600 m depth, a 150-200 tonnes rig, and 30 days of operation. It is assumed there are 1.5 years between exploration well results and final completion with a new and lighter rig for completion of 2.8 M€ based on the current cost of a drilled well in La Rioja (Spain). A new injector well costs 6.9 M€. Reception and injection facilities have similar investment costs but OPEX's are reduced by using internal energy (solar panels); these ranges from 5.5 M€/year to 2.6 M€/year.

Finally, cost estimation and conditions for the reception and injection facilities have been estimated assuming an onshore pipeline, CO_2 transported in dense phase to the site at 30 ºC and 85 bars, reception tanks, transport, and pumping to the wellhead with injection at 41 ºC and 174 bars, with an estimated cost of 11.2 M€ investment and 2.5 M€/year OPEX.

5.3.3 Economic results and prioritization

The economic evaluation has been carried out using PetroVR® software in a deterministic way for the 3 cases (2.1 Mt, 4.2 Mt, and 23 Mt); 3 scenarios (MI, FIK, and GD); and 3 prices (BP, HP, and LP). To compare the scenarios, multiple parameters have been analysed, and 3 of them have been selected to reach a final decision: maximum cash out (Figure 5.24); deterministic NPV for low capacity (4 Mt) (Figure 5.20) and high capacity (23 Mt) (Figure 5.23).

The results for the **low-capacity** cases show negative results (NPV, 9%) except for high price, 4 Mt-case, and assuming as income ETS market price for a tonne of CO_2.

4 Mt capacity	Minimum Investment (MI)	First of its kind (FIK)	Green development (GD)
NPV (9%)- BP (€ million)	-5.7	**1.2**	-0.1
NPV (9%)- HP (€ million)	**42.3**	**78.9**	**77.2**
NPV (9%)- LP (€ million)	-33.0	-48.5	-49.5

Table 5.10 NPV results for 4 Mt-case and 3 scenarios assuming ETS market price for a CO_2 tonne.

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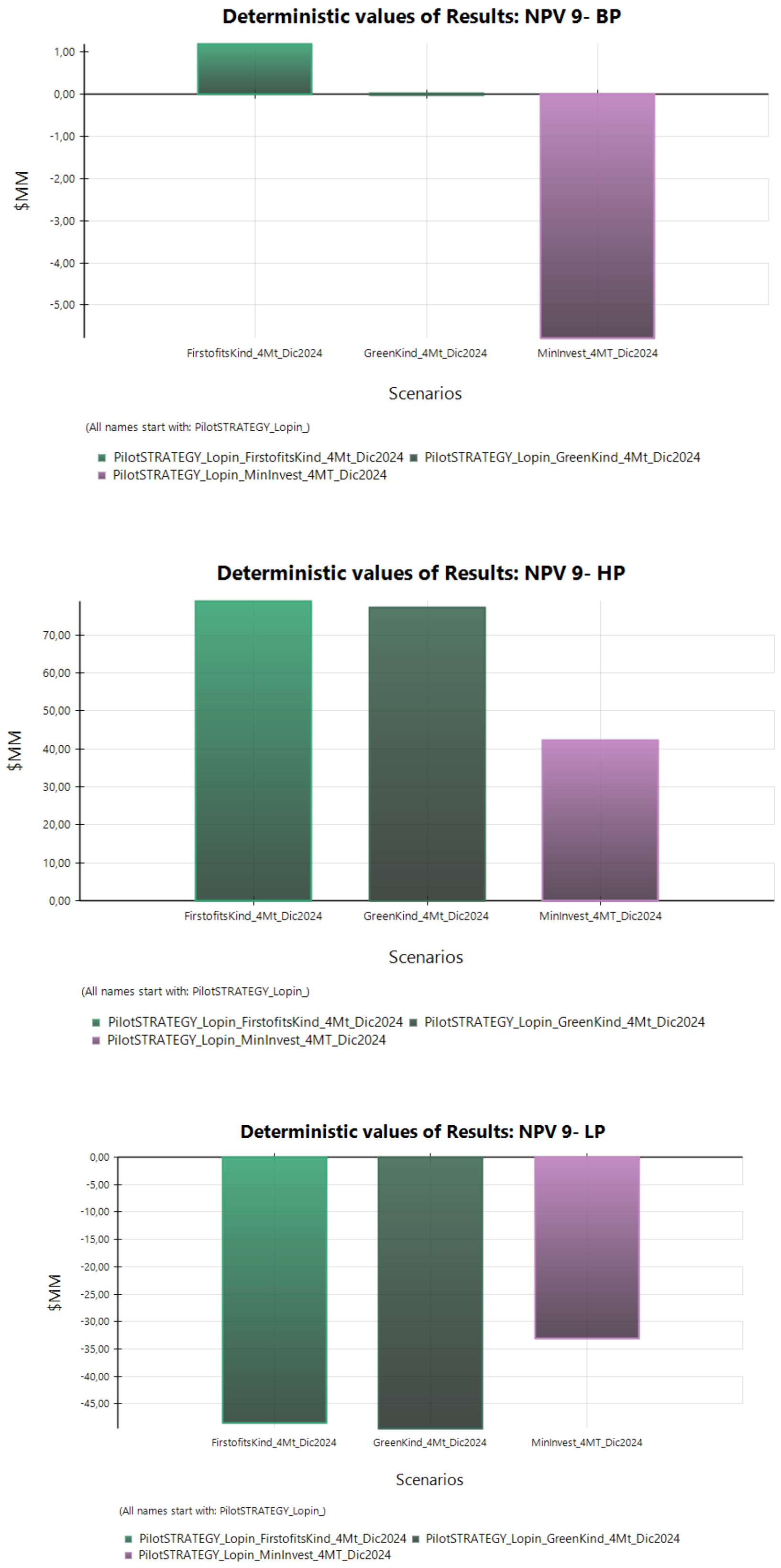

Figure 5.20 NPV (9%, 2025) of 4 Mt-case and 3 scenarios assuming ETS market price.

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Focus on the 4 Mt-case (with sensible better results than the 2 Mt-case) and calculating the CO_2 price breakeven for the Base, High and Low price (i.e., the % of CO_2 price at ETS Market that must be dedicated to storage operation for a positive NPV(9%)[13]). The % of CO_2 price to be dedicated to storage is between 90% (2.1 Mt-case & FIK) to 60% (4.2 Mt-case & GD, FIK), that is, a **storage fee** between 180 to 120 €/tonne in 2030 (Figure 5.21).

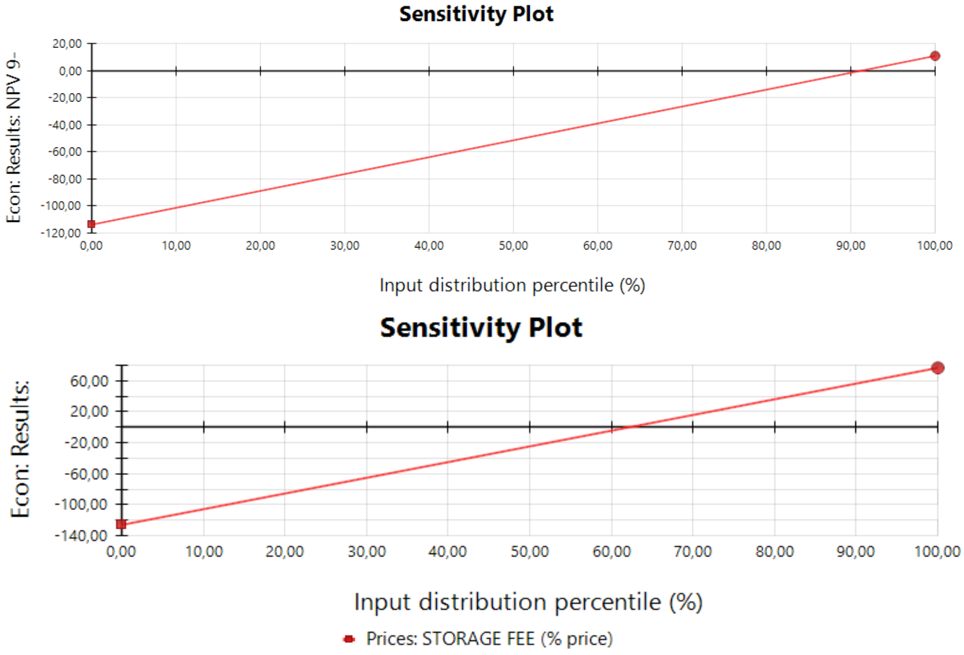

Figure 5.21 Breakeven for 2.1 Mt & FIK (up) and 4 Mt & GD (down) scenario as % respect ETS Market price.

For the 23 Mt-case, results show more promising values assuming income from 1 tonne CO_2 stored at ETS market price:

23 Mt capacity	Minimum Investment (MI)	First of its kind (FIK)	Green development (GD)
NPV (9%)- BP (€ million)	**344**	**506**	**535**
NPV (9%)- HP (€ million)	**644**	**967**	**996**
NPV (9%)- LP (€ million)	**161**	**198**	**228**

Table 5.11 NPV results for 23 Mt-case and 3 scenarios assuming ETS market price for CO2 tonne.

And assuming **20% of ETS market price as storage fee** (that is, 20% of CO_2 price dedicated to storage operation), only GD and MI scenarios are positive in the base-case and all in the high-case:

---

[13] CO_2 ETS Market price is used for the evaluation of the full chain capture, transport, and storage. Ebro Basin scenarios are focused only on the storage step, so it is relevant which percentage of it must be dedicated to storage for a positive result. In general terms, storage operation takes between 5% and 20% of total costs for the CCS full channel.

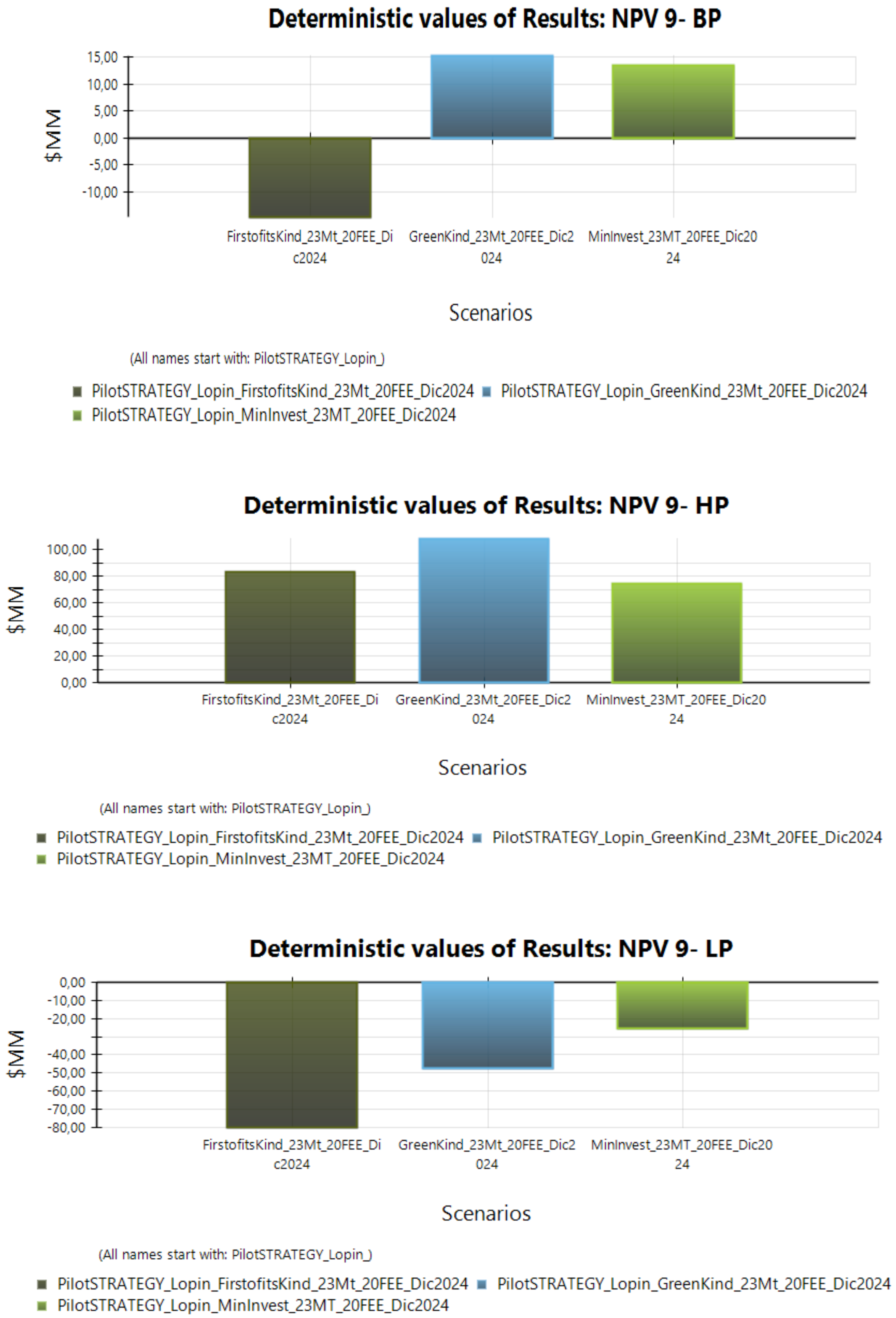

Figure 5.22 NPV (9%, 2025) for the 23 Mt-case and assuming 20% of storage fee respect ETS Market price.

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The evaluation of the breakeven as storage fee for all cases shows the Minimum Investment (MI) case as the most robust in terms of the storage fee:

Price (100% ETS Market)	FIK	GD	MI
Base price	30%	20%	**20%**
Low price	50%	38%	**35%**
High Price	18%	12%	**12%**

Table 5.12 Breakeven as % of ETS market rice for positive NPV (9%, 2025) and 23 Mt-case

Taking the 23 Mt-case with 20% storage fee and base price as example, the cash flow[14] analysis show earlier but lower investment in the Minimum Investment scenario and becoming faster positive, with lower but longer injection period. The other two scenarios look very similar initially (investment, cash-out) although better results at long term of the Green Development scenario (Figure 5.23).

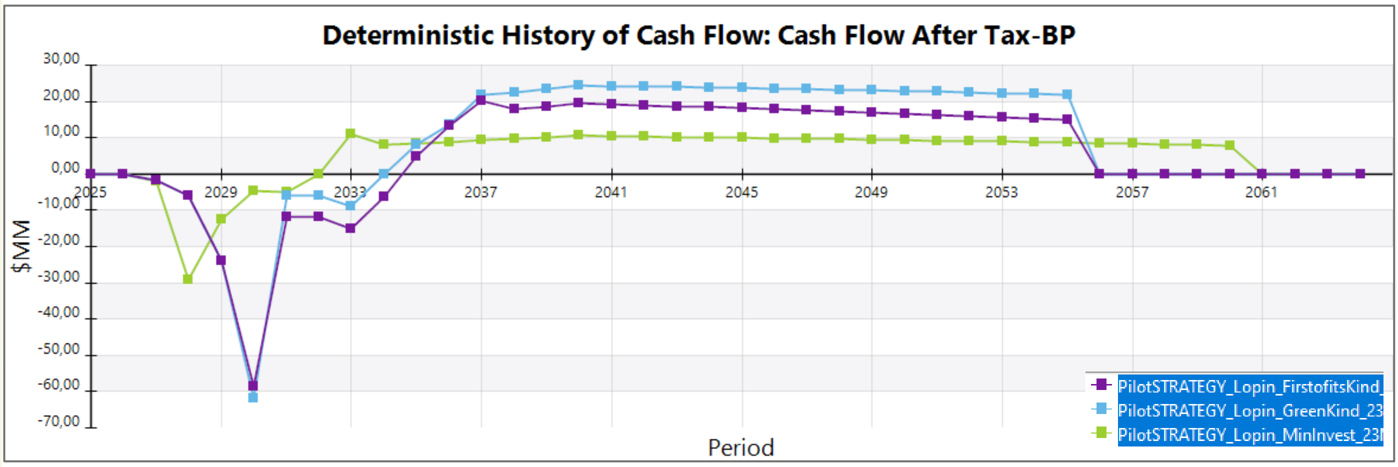

Figure 5.23 Cash-flow for 23 Mt-case, Base price and 20% of ETS Market price as storage fee. ($MM= Million USD)

About the max cash out, the MI scenario presents the lower max cash flow out for both the 4 Mt-case and the 23 Mt-case, and both are very similar:

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[14] Spain doesn´t have specific CO_2 taxes. It was applied 30% taxes as general taxes.

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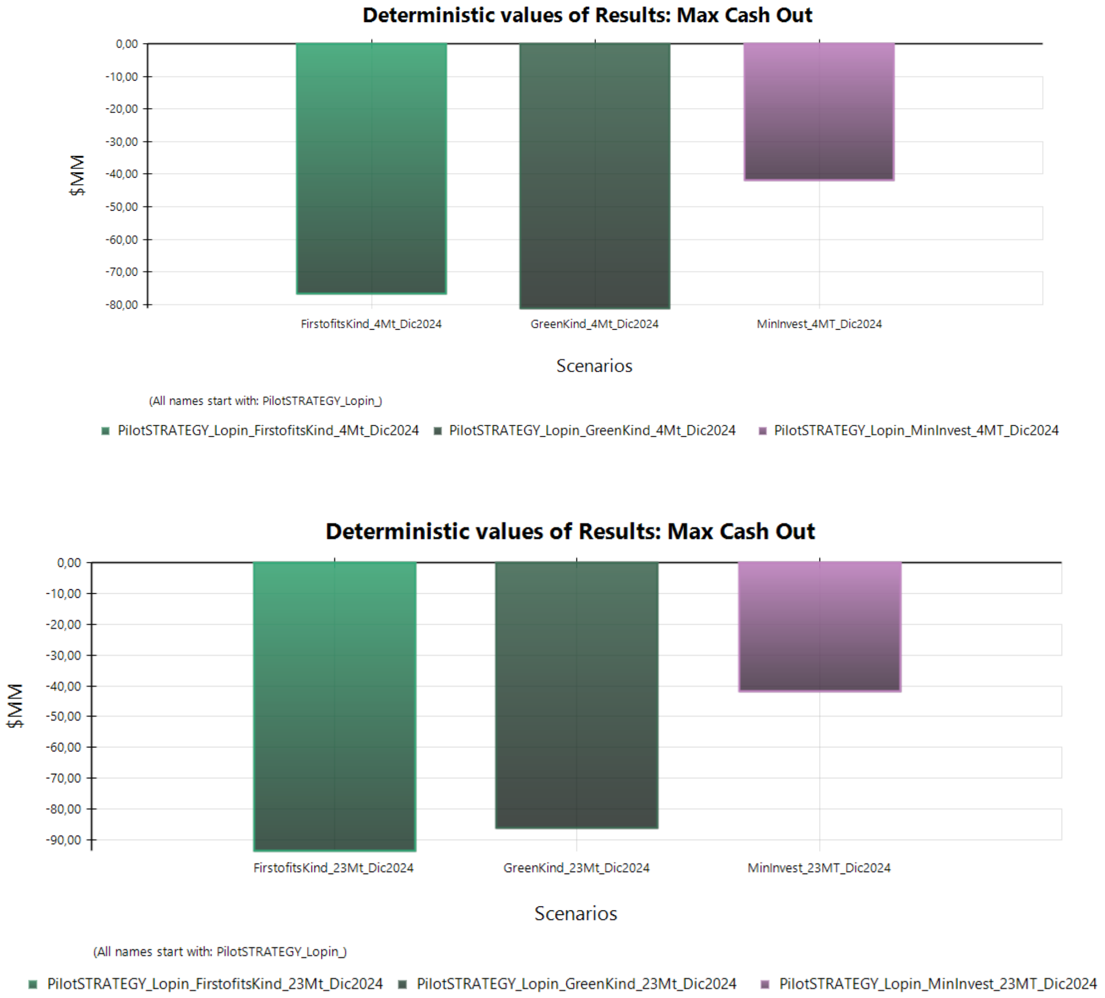

Figure 5.24 Maximum cash out, comparison for the three scenarios ($MM= Million EUR) at 4 Mt-case (up) and 23 Mt-case (down)

5.3.4 Final development selection

The economic evaluation has tried to identify the better strategy to apply considering current information available. The main uncertainty is the estimated capacity and whether or not existing compartmentalisation limits maximum injection rate and total volume. Based on it, the evaluation shows economic results for NPV (9%, 2025) for the 2 Mt, 4 Mt, and 23 Mt cases and identifies that NPV is highly dependent on storage prices and breakeven. Based on it, the Minimum Investment scenario is the most robust case for the different prices.

Based on cash-flow, cash-out and flexibility, the Minimum Investment case presents lower initial investment and faster recuperation than the other two scenarios to a positive balance. In the long term, the Green Development shows better income results and positive parameters.

The Minimum Investment scenario is, therefore, the preferred scenario. It has the following advantages over the other two scenarios:

- Minimum initial investment adaptable both for low capacities and higher capacities.
- It is the most robust based on breakeven prices.
- Simplified development phases and operations, therefore reducing the project's complexity.
- Lower local impact and easier social acceptance.
- Adaptable to any source including low volume and DAC (direct air capture).

5.4 Upper Silesia Basin (Poland) conceptual scenarios

The Polish case considers a pilot scale injection of CO_2 at the rate of 30 kt/y through 3 years and then upscaling to a commercial plant with an injection 300 kt/y through 25 years.

5.4.1 Scenario/s selection rationale

The objective of the task was a simplified economic evaluation to have a first overview of the project economics. The life-cycle approach taking into account the pilot phase as well as the commercial phase was considered for economic evaluation to provide important information to policy-makers, scientists, and engineers enabling assessment of the technology. An effort to catch the complexity of the process was made to describe the cost and benefits of CCS, however, at this stage of the assessment, the cost valuation was made using the indicative and simplified method.

The simplified economic evaluation was performed for the one conceptual scenario, which was identified during a framing session phase conducted previously in the project and summarised in the D4.2 public deliverable "Conceptual scenarios definition to enable decision support" (Canteli et al., 2024). This report assesses the economics of the scenario 'Pilot for commercial development to attract developers'. The Table 5.13 presents basic decisions foreseen for the selected scenario.

Table 5.13 The conceptual scenario 'Pilot for commercial development to attract developers' selected to simplified economic evaluation

CO_2 **Source**	**Transport**	CO_2 **Quantity**	**Supply continuity**	**Monitoring**	**Power Supply**	**well design**
Power plants (1)	road – during pilot	research project - to 100 kt	continuous	according to law	Polish power grids	new vertical
Heating plants	pipeline – commercial scale	commercial - to capacity of deposit 40-60 Mt	intermittent		renewables	new deviated
Waste incineration plants		min. to obtain results ~30kt			power generators	
Other industrial emitters (2)						

(1) Power plants (Tauron, PGE Rybnik, Bełchatów, Enea Połaniec).

(2) other industrial emitters nearby: Steel mill Dąbrowa Górnicza; cement plants (Holcim Małogoszcz, Dyckerhoff, Cemex Rudniki, Warta, Górażdże); Chemical plants (Synthos, Azoty).

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The main assumptions of the scenario were as follows:

- implementation of CCS technology in a pilot installation on a scale of up to 100 kt to attract investors and prove economic and technical viability and then transforming the pilot into a commercial installation
- assumption that industry representatives who need to remove process emissions and who do not have an alternative may be interested, e.g. steelworks, cement plants, chemical plants, large waste incineration plants will be CO_2 sources – such plants are located from 30 to 80 km from the storage site
- A continuous CO_2 injection was assumed in the commercial phase. During the pilot phase road transport is expected, and after increasing the scale, transport by pipeline. Preparation for pipeline construction should begin during the pilot phase

Table 5.14 Assumption considered in pilot and commercial phases.

Assumption	Pilot phase	Commercial phase
Amount of CO_2	30 kt/y	300 kt/y
Transport	road	pipeline
Tank trucks	4*25 t/d=100 t/d * 300 d = 30 kt/y	
Duration (injection period, years)	3	25
Total amount of CO2 injected during both phases	7.59 Mt	
Capacity of the storage site	30 Mt	

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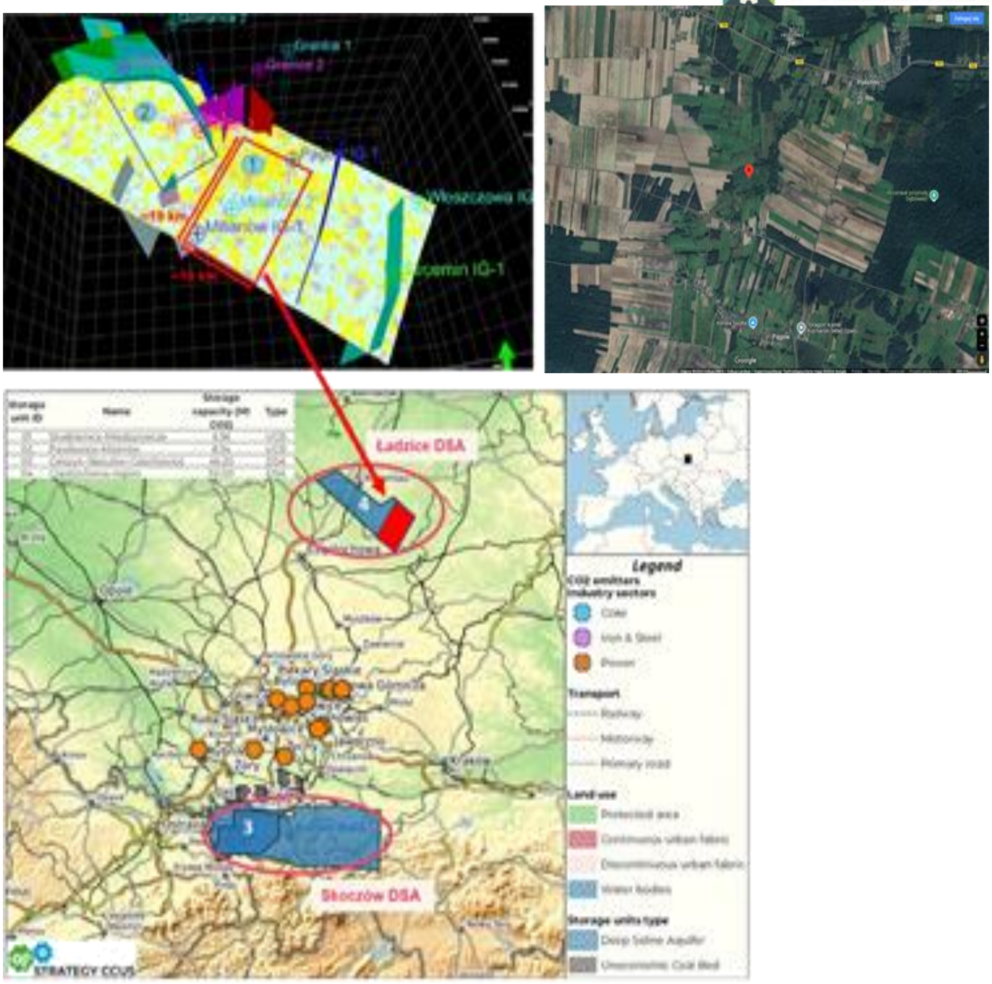

Figure 5.25 Storage site location

5.4.2 Techno-economic description (actions, schedule and costs)

As a result of the modelling performed as part of WP3, the IN-1A injection well was selected, for which in the optimal scenario max. storage capacity is 31.27 Mt, an average thickness of 63.8 m, an average porosity of 14.90 – 19.29%, and an average permeability of 153.8 – 955.9 mD. The area of the "Pągów-Milianów" deposit (Figure 5.25) in Ładzice DSA - Jurassic Czestochowa District is approximately 190 km^2. The following initial conditions were considered during modelling: Average temperature 38.0°C, initial reservoir pressure 108 bar, reference depth 1000 m. Calculation of the demand for electricity for injection was calculated using the Excel tool developed in the project Strategy CCUS[15] with these assumptions.

The techno-economic analysis was performed for a 33-year period covering the following phases:

- geological surveys, modelling, preparation of technical documentation and obtaining the necessary administrative decisions: 3 years,
- pilot installation implementation: 2 years,
- pilot installation operation: 3 years,

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[15] STRATEGY CCUS (H2020-LC-SC3-2018-2019-2020/H2020-LC-SC3-2018-NZE-CC) https://strategyccus.brgm.fr/

- commercial installation implementation: 2 years,
- commercial installation operation: 25 years.

Pursuant to the Polish geological and mining law (Journal of Laws 2024.1290, consolidated text[16]), there is an obligation to monitor the underground carbon dioxide storage complex for a period of not less than 20 years after the closure of the underground carbon dioxide storage site, which was considered in the calculations.

Investment expenditure (CAPEX) were estimated based on the results of the work carried out within the STRATEGY CCUS project and available literature data. They are summarized in table 5.15.

Table 5.15 Estimated CAPEX of the pilot and commercial phases for Upper Silesia Basin (Poland) - price level 2025

Item	Unit	Amount
3D seismic research	MEUR	2.70
Modelling, technical documentation, permits and administrative decisions (including environmental decisions)	MEUR	0.90
Wells - drilling + completion	pcs	1.00
	MEUR/pcs	7.20
	MEUR	7.20
Pipeline	km	80.00
	MEUR/km	2.30
	MEUR	184.00
Land, infrastructure on the ground surface - pilot phase	MEUR	4.50
Land, infrastructure on the ground surface - commercial phase	MEUR	9.00

Due to the very low level of investment advancement (study phase), a contingency of 20% of CAPEX was included in the calculations.

Based on the technical assumptions presented in Chapter 5.4.1, the results of the STRATEGY CCUS project and current market prices in Poland, the operating costs including CO_2 capture, transport and injection into the underground reservoir were estimated. The calculation assumptions and unit operating costs are presented in *Table 5.16*.

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[16] https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=wdu20111630981

Table 5.16: Estimated OPEX of the pilot and commercial phases for Upper Silesia Basin (Poland) - price level 2025

Item	Unit	Amount
Duration – pilot phase	year	3
Duration - commercial phase	year	25
Electricity - pilot phase	MWh/3 years	154.03
	MWh/year	51.34
Electricity - commercial phase	MWh/25 years	12,835.83
	MWh/year	513.43
Monitoring	MEUR/year	4.50
Salaries	posts/shift	4
	shifts	3
	EUR/month	1,400
	EUR/year	201,600
Local taxes, insurance	% of CAPEX	2%
Maintenance and repairs - pilot phase	MEUR/year	0.09
Maintenance and repairs - commercial phase	MEUR/year	0.18
Cost of CO_2 capture	EUR/t CO_2	12.00
Cost of CO_2 transport (road)	km	80.00
	EUR/km/t CO_2	0.23
Cost of CO_2 transport (pipeline)	km	80.00
	EUR/km/t CO_2	0.01
CO_2 injection - pilot	t/year	30,000
CO_2 injection - commercial	t/year	300,000

For the purpose of calculating economic efficiency indicators, OPEX components were adjusted for the inflation rate. The calculation assumptions and price forecasts used to calculate the economic efficiency indicators (NPV, IRR) are *presented in*

Table 5.17.

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Table 5.17 : Calculation assumptions and forecasts used for OPEX calculations

Item	Unit	Amount																
		2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
CO_2 price - base	EUR/t	75.00	80.00	85.00	90.00	95.00	100.00	103.00	106.00	109.00	112.00	115.00	118.00	121.00	124.00	127.00	130.00	130.00
CO_2 price - low	EUR/t	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00
CO_2 price - high	EUR/t	75.00	101.00	127.00	153.00	179.00	205.00	209.00	213.00	217.00	221.00	225.00	226.00	227.00	228.00	229.00	230.00	230.00
Electricity price	EUR/ MWh	75.00	77.00	79.00	81.00	83.00	85.00	85.00	85.00	85.00	85.00	85.00	85.86	86.72	87.58	88.44	89.30	90.18
Inflation	%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%

Item	Unit	Amount															
		2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052	2053	2054	2055	2056	2057
CO_2 price - base	EUR/t	130.00	130.00	130.00	130.00	130.00	130.00	130.00	130.00	130.00	130.00	130.00	130.00	130.00	130.00	130.00	130.00
CO_2 price - low	EUR/t	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00	75.00
CO_2 price - high	EUR/t	230.00	230.00	230.00	230.00	230.00	230.00	230.00	230.00	230.00	230.00	230.00	230.00	230.00	230.00	230.00	230.00
Electricity price	EUR/ MWh	91.06	91.94	92.82	93.70	94.64	95.58	96.52	97.46	98.40	98.40	98.40	98.40	98.40	98.40	98.40	98.40
Inflation	%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%	2.20%

5.4.3 Economic results and prioritisation

In order to assess the economic efficiency of the analysed concept of CO_2 capture, transport and injection into the underground reservoir, the NPV and IRR indices were calculated for three scenarios of forecast prices of CO_2 emission allowances purchase:

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

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

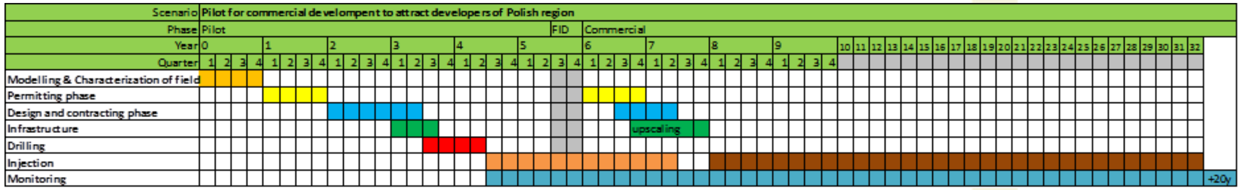
Table 5.18 presents the estimated CAPEX and OPEX for the period covered by the analysis and the cash flows used to calculate NPV and IRR. A discount rate of 9% was used in the calculations.

Table 5.18: CAPEX, OPEX and cash flow used for economic efficiency calculations

Item	Unit	Pilot							
		2025	2026	2027	2028	2029	2030	2031	2032
3D seismic research, technical documentation, permits and administrative decisions (including	MEUR	1.08	1.10	2.26					
CAPEX - pilot phase	MEUR				7.49	7.66			
CAPEX - commercial phase	MEUR							131.95	134.85
Electricity	MEUR					25.67	51.34	51.34	25.67
	MEUR					0.0021	0.0044	0.0044	0.0022
CO_2 capture	MEUR					0.196	0.401	0.410	0.210
CO_2 transport (road)	MEUR					0.301	0.615	0.629	0.321
CO_2 transport (pipeline)	MEUR								
Salaries	MEUR					0.220	0.225	0.230	0.235
Local taxes, insurance	MEUR					0.303	0.303	0.303	0.303
Maintenance and repairs	MEUR					0.098	0.100	0.103	0.105
Monitoring	MEUR					4.909	5.017	5.128	5.240
CO_2 injection	t					15,000	30,000	30,000	15,000
Revenue - avoided ETS costs - base CO_2 price	MEUR					1.425	3.000	3.090	1.590
Revenue - avoided ETS costs - low CO_2 price	MEUR					1.125	2.250	2.250	1.125
Revenue - avoided ETS costs - high CO_2 price	MEUR					2.685	6.150	6.270	3.195
Cash flow - pilot phase - base CO_2	**MEUR**	**-1.080**	**-1.104**	**-2.256**	**-7.494**	**-12.263**	**-3.667**	**-3.717**	**-4.826**
Cash flow - pilot phase - low CO_2	**MEUR**	**-1.080**	**-1.104**	**-2.256**	**-7.494**	**-12.563**	**-4.417**	**-4.557**	**-5.291**
Cash flow - pilot phase - high CO_2	**MEUR**	**-1.080**	**-1.104**	**-2.256**	**-7.494**	**-11.003**	**-0.517**	**-0.537**	**-3.221**
Cash flow - total - base CO_2 price	**MEUR**	**-1.080**	**-1.104**	**-2.256**	**-7.494**	**-12.263**	**-3.667**	**-135.668**	**-139.681**
Cash flow - total - low CO_2 price	**MEUR**	**-1.080**	**-1.104**	**-2.256**	**-7.494**	**-12.563**	**-4.417**	**-136.508**	**-140.146**
Cash flow - total - high CO_2 price	**MEUR**	**-1.080**	**-1.104**	**-2.256**	**-7.494**	**-11.003**	**-0.517**	**-132.488**	**-138.076**
Discounted cash flow - pilot phase - base CO_2 price	**MEUR**	**-1.080**	**-1.013**	**-1.899**	**-5.786**	**-8.688**	**-2.383**	**-2.216**	**-2.640**
Discounted cash flow - pilot phase - low CO_2 price	**MEUR**	**-1.080**	**-1.013**	**-1.899**	**-5.786**	**-8.900**	**-2.871**	**-2.717**	**-2.895**
Discounted cash flow - pilot phase - high CO_2 price	**MEUR**	**-1.080**	**-1.013**	**-1.899**	**-5.786**	**-7.795**	**-0.336**	**-0.320**	**-1.762**
Discounted cash flow - total - base CO_2 price	**MEUR**	**-1.080**	**-1.013**	**-1.899**	**-5.786**	**-8.688**	**-2.383**	**-80.894**	**-76.410**
Discounted cash flow - total - low CO_2 price	**MEUR**	**-1.080**	**-1.013**	**-1.899**	**-5.786**	**-8.900**	**-2.871**	**-81.395**	**-76.664**
Discounted cash flow - total - high CO_2 price	**MEUR**	**-1.080**	**-1.013**	**-1.899**	**-5.786**	**-7.795**	**-0.336**	**-78.998**	**-75.532**

Item	Unit	Commercial												
		2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045
3D seismic research, technical documentation, permits and administrative decisions (including	MEUR													
CAPEX - pilot phase	MEUR													
CAPEX - commercial phase	MEUR													
Electricity	MEUR	513.43	513.43	513.43	513.43	513.43	513.43	513.43	513.43	513.43	513.43	513.43	513.43	513.43
	MEUR	0.0436	0.0436	0.0436	0.0441	0.0445	0.0450	0.0454	0.0458	0.0463	0.0468	0.0472	0.0477	0.0481
CO_2 capture	MEUR	4.285	4.379	4.475	4.574	4.674	4.777	4.882	4.990	5.099	5.212	5.326	5.443	5.563
CO_2 transport (road)	MEUR													
CO_2 transport (pipeline)	MEUR	0.286	0.292	0.298	0.305	0.312	0.318	0.325	0.333	0.340	0.347	0.355	0.363	0.371
Salaries	MEUR	0.240	0.245	0.251	0.256	0.262	0.268	0.273	0.279	0.286	0.292	0.298	0.305	0.312
Local taxes, insurance	MEUR	5.639	5.639	5.639	5.639	5.639	5.639	5.639	5.639	5.639	5.639	5.639	5.639	5.639
Maintenance and repairs	MEUR	0.214	0.219	0.224	0.229	0.234	0.239	0.244	0.249	0.255	0.261	0.266	0.272	0.278
Monitoring	MEUR	5.356	5.474	5.594	5.717	5.843	5.971	6.103	6.237	6.374	6.514	6.658	6.804	6.954
CO_2 injection	t	300,000	300,000	300,000	300,000	300,000	300,000	300,000	300,000	300,000	300,000	300,000	300,000	300,000
Revenue - avoided ETS costs - base CO_2 price	MEUR	32.700	33.600	34.500	35.400	36.300	37.200	38.100	39.000	39.000	39.000	39.000	39.000	39.000
Revenue - avoided ETS costs - low CO_2 price	MEUR	22.500	22.500	22.500	22.500	22.500	22.500	22.500	22.500	22.500	22.500	22.500	22.500	22.500
Revenue - avoided ETS costs - high CO_2 price	MEUR	65.100	66.300	67.500	67.800	68.100	68.400	68.700	69.000	69.000	69.000	69.000	69.000	69.000
Cash flow - pilot phase - base CO_2	**MEUR**													
Cash flow - pilot phase - low CO_2	**MEUR**													
Cash flow - pilot phase - high CO_2	**MEUR**													
Cash flow - total - base CO_2 price	**MEUR**	**16.637**	**17.309**	**17.975**	**18.636**	**19.292**	**19.943**	**20.588**	**21.227**	**20.960**	**20.688**	**20.410**	**20.126**	**19.835**
Cash flow - total - low CO_2 price	**MEUR**	**6.437**	**6.209**	**5.975**	**5.736**	**5.492**	**5.243**	**4.988**	**4.727**	**4.460**	**4.188**	**3.910**	**3.626**	**3.335**
Cash flow - total - high CO_2 price	**MEUR**	**49.037**	**50.009**	**50.975**	**51.036**	**51.092**	**51.143**	**51.188**	**51.227**	**50.960**	**50.688**	**50.410**	**50.126**	**49.835**
Discounted cash flow - pilot phase - base CO_2 price	**MEUR**													
Discounted cash flow - pilot phase - low CO_2 price	**MEUR**													
Discounted cash flow - pilot phase - high CO_2 price	**MEUR**													
Discounted cash flow - total - base CO_2 price	**MEUR**	**8.350**	**7.969**	**7.593**	**7.222**	**6.859**	**6.505**	**6.161**	**5.828**	**5.279**	**4.780**	**4.327**	**3.914**	**3.539**
Discounted cash flow - total - low CO_2 price	**MEUR**	**3.231**	**2.859**	**2.524**	**2.223**	**1.953**	**1.710**	**1.492**	**1.298**	**1.123**	**0.968**	**0.829**	**0.705**	**0.595**
Discounted cash flow - total - high CO_2 price	**MEUR**	**24.610**	**23.025**	**21.533**	**19.778**	**18.165**	**16.682**	**15.318**	**14.064**	**12.835**	**11.713**	**10.687**	**9.749**	**8.892**

Item	Unit	Commercial												Monitoring	
		2046	2047	2048	2049	2050	2051	2052	2053	2054	2055	2056	2057	2058	2077
3D seismic research, technical documentation, permits and administrative decisions (including	MEUR														
CAPEX - pilot phase	MEUR														
CAPEX - commercial phase	MEUR														
Electricity	MEUR	513.43	513.43	513.43	513.43	513.43	513.43	513.43	513.43	513.43	513.43	513.43	513.43		
	MEUR	0.0486	0.0491	0.0496	0.0500	0.0505	0.0505	0.0505	0.0505	0.0505	0.0505	0.0505	0.0505		
CO_2 capture	MEUR	5.686	5.811	5.938	6.069	6.203	6.339	6.479	6.621	6.767	6.916	7.068	7.223		
CO_2 transport (road)	MEUR														
CO_2 transport (pipeline)	MEUR	0.379	0.387	0.396	0.405	0.414	0.423	0.432	0.441	0.451	0.461	0.471	0.482		
Salaries	MEUR	0.318	0.325	0.333	0.340	0.347	0.355	0.363	0.371	0.379	0.387	0.396	0.405		
Local taxes, insurance	MEUR	5.639	5.639	5.639	5.639	5.639	5.639	5.639	5.639	5.639	5.639	5.639	5.639		
Maintenance and repairs	MEUR	0.284	0.291	0.297	0.303	0.310	0.317	0.324	0.331	0.338	0.346	0.353	0.361		
Monitoring	MEUR	7.107	7.263	7.423	7.586	7.753	7.924	8.098	8.276	8.458	8.644	8.835	9.029	9.228	13.953
CO_2 injection	t	300,000	300,000	300,000	300,000	300,000	300,000	300,000	300,000	300,000	300,000	300,000	300,000		
Revenue - avoided ETS costs - base CO_2 price	MEUR	39.000	39.000	39.000	39.000	39.000	39.000	39.000	39.000	39.000	39.000	39.000	39.000		
Revenue - avoided ETS costs - low CO_2 price	MEUR	22.500	22.500	22.500	22.500	22.500	22.500	22.500	22.500	22.500	22.500	22.500	22.500		
Revenue - avoided ETS costs - high CO_2 price	MEUR	69.000	69.000	69.000	69.000	69.000	69.000	69.000	69.000	69.000	69.000	69.000	69.000		
Cash flow - pilot phase - base CO_2	**MEUR**														
Cash flow - pilot phase - low CO_2	**MEUR**														
Cash flow - pilot phase - high CO_2	**MEUR**														
Cash flow - total - base CO_2 price	**MEUR**	**19.538**	**19.235**	**18.924**	**18.607**	**18.283**	**17.953**	**17.615**	**17.270**	**16.917**	**16.556**	**16.188**	**15.811**	**-9.228**	**-13.953**
Cash flow - total - low CO_2 price	**MEUR**	**3.038**	**2.735**	**2.424**	**2.107**	**1.783**	**1.453**	**1.115**	**0.770**	**0.417**	**0.056**	**-0.312**	**-0.689**	**-9.228**	**-13.953**
Cash flow - total - high CO_2 price	**MEUR**	**49.538**	**49.235**	**48.924**	**48.607**	**48.283**	**47.953**	**47.615**	**47.270**	**46.917**	**46.556**	**46.188**	**45.811**	**-9.228**	**-13.953**
Discounted cash flow - pilot phase - base CO_2 price	**MEUR**														
Discounted cash flow - pilot phase - low CO_2 price	**MEUR**														
Discounted cash flow - pilot phase - high CO_2 price	**MEUR**														
Discounted cash flow - total - base CO_2 price	**MEUR**	**3.198**	**2.889**	**2.607**	**2.352**	**2.120**	**1.910**	**1.719**	**1.546**	**1.390**	**1.248**	**1.119**	**1.003**	**-0.537**	**-0.158**
Discounted cash flow - total - low CO_2 price	**MEUR**	**0.497**	**0.411**	**0.334**	**0.266**	**0.207**	**0.155**	**0.109**	**0.069**	**0.034**	**0.004**	**-0.022**	**-0.044**	**-0.537**	**-0.158**
Discounted cash flow - total - high CO_2 price	**MEUR**	**8.109**	**7.394**	**6.741**	**6.144**	**5.599**	**5.102**	**4.648**	**4.233**	**3.854**	**3.509**	**3.194**	**2.906**	**-0.537**	**-0.158**



The results of the economic efficiency calculations for the analysed scenario of CO_2 capture, transport and injection into the underground reservoir are summarized in Table 5.19.

Table 5.19: Summary of the results of economic efficiency calculations for the analysed scenario of CO_2 capture, transport and injection into the underground reservoir

PILOT PHASE						
Scenario	**CAPEX**		**OPEX**		**NPV**	**IRR**
	M EUR	**EUR/t CO_2**	**M EUR**	**EUR/t CO_2**	**M EUR**	**%**
Scenario 1 - base CO_2 price	19.59	217.69	25.92	287.99	-25.70	non-existent
Scenario 2 - low CO_2 price					-27.16	non-existent
Scenario 3 - high CO_2 price					-19.99	non-existent
TOTAL - PILOT + COMMERCIAL PHASE + MONITORING (20 years)						
Scenario	**CAPEX**		**OPEX**		**NPV**	**IRR**
	M EUR	**EUR/t CO_2**	**M EUR**	**EUR/t CO_2**	**M EUR**	**%**
Scenario 1 - base CO_2 price	286.40	37.73	737.92	97.22	-82.96	non-existent
Scenario 2 - low CO_2 price					-162.31	non-existent
Scenario 3 - high CO_2 price					89.81	14.6%

The obtained results indicate that the investment is economical only when the commercial phase is included in the calculations and in the case of the scenario with the highest prices of CO_2 emission allowances. The pilot phase is not effective for any CO_2 price scenario. But this is in line with expectations - the pilot phase is to demonstrate that CO_2 injection is technically feasible and that a commercial phase can be implemented.

5.4.4 Final development selection

The preliminary schedule includes the pilot phase as well as the commercial phase:

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

5.5 Macedonia Basin (Greece) conceptual scenarios

5.5.1 Scenario/s selection rationale

With the current Energy transition plan implemented by the Greek Ministry of Energy most of power plants using coal are set to be decommissioned by 2025 with Ptolemaida V remaining operational till 2028[17]. Thus, they will be no large emitters/producers of CO_2 to sustain a local market in the West Macedonia . Most of the other large industrial emitters are scattered across Greece. Still, the case of Mesohellenic Basin (MHB) presents commercial interest for CO_2 storage development. This is mainly based on the following paramount factors:

1) Stakeholders and social acceptance
2) Industrial infrastructure present and available
3) The area where the current infrastructure is located holds the necessary permits for industrial works thus enabling quick transition avoiding the lengthy procedures.
4) Specialised workforce
5) Proximity with large industrial emitters coming from other countries like Italy, Serbia, Bulgaria, Turkey.
6) Already available pipeline corridors with existing permits in force.

As such, the MHB could serve as a regional storage solution, enabling neighbouring countries to store CO_2 under optimal conditions. This would support South-east Europe's progress toward achieving net-zero emissions, creating a win-win scenario where local and national stakeholders collaborate in mutually beneficial partnerships. Given the aforementioned, the scenarios presented in this section are concerned with CO_2 transport and CO_2 storage in saline aquifers. The current infrastructure of Agios Dimitrios and Ptolemaida can be used as a CO_2 hub where it will be collected from various places.

Pipelines are the most common method for transporting large volumes of CO_2, especially over short to medium distances. For the Western Macedonia region, this would likely be the most efficient and cost-effective solution due to several advantages:

- Efficiency, pipelines offer continuous transport and can handle large volumes of CO_2.
- Cost-Effective Over Short/Medium Distances, though expensive to install, pipelines become cost-effective when transporting large volumes of CO_2 over distances under 500 km.
- Existing Infrastructure, the region already has some industrial infrastructure in place due to its lignite power plants and mining operations, which might facilitate the construction of CO_2 pipelines.
- Topography considerations, while the region is hilly, it is feasible to build pipelines with modern technology that can adapt to local conditions.

Proposed Pipeline Routes (Figure 5.26):

- This would involve constructing a pipeline that runs roughly 50–60 km northwest from Agios Dimitrios to Pentalofos.

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[17] Ministry of the Environment and Energy, National Energy and Climate Plan (NECP) - revised edition. 2024: Athens.

- Ptolemaida V to Eptachori. Eptachori is further to the west, with a pipeline distance of approximately 80–100 km. A longer pipeline would be necessary here, but still manageable.

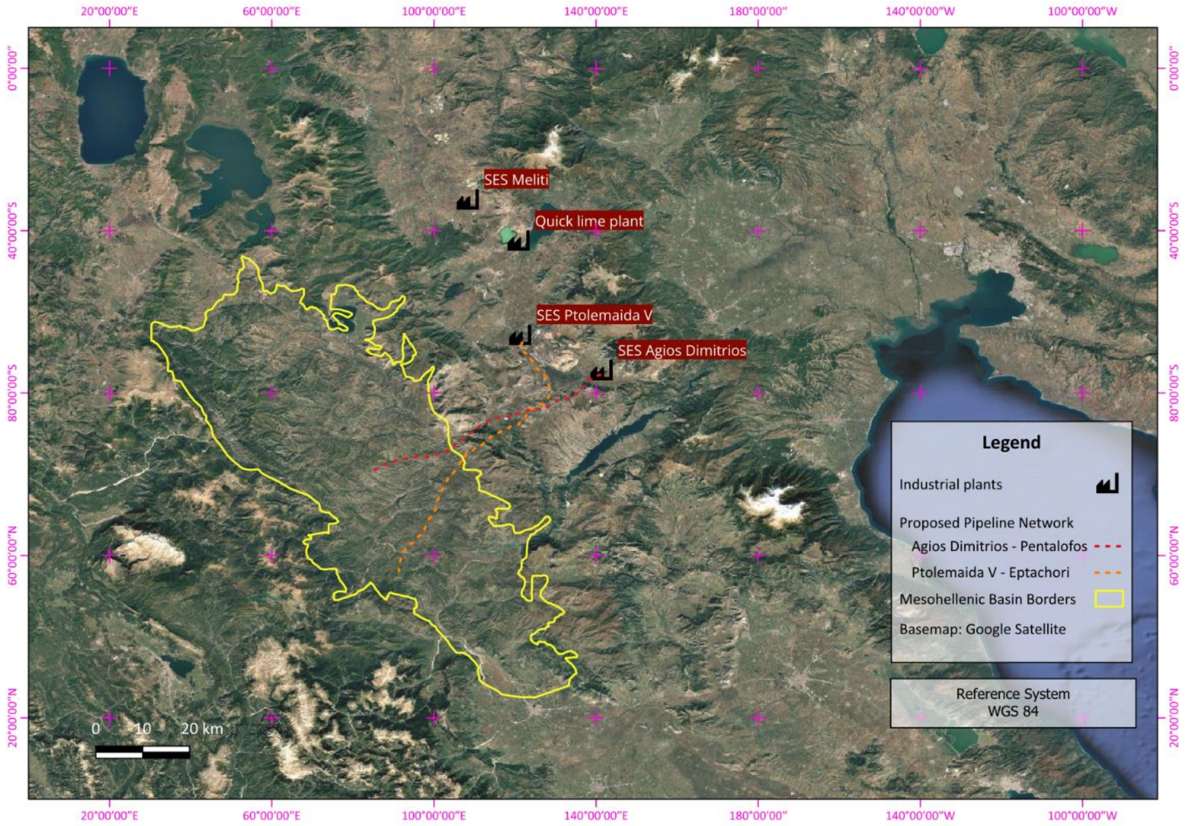

Figure 5.26: Location map of the Mesohellenic Basin, industrial plants and suggested pipelines.

Given the distance, pipelines are likely the most suitable option for both storage sites. Additional compression stations may be required, depending on the terrain.

Transport by truck CO_2 in liquefied form is another possible transportation method, particularly over short distances or for smaller volumes. This approach is less efficient for large-scale projects due to the logistical challenges, including:

- Trucks can only carry limited quantities of liquefied CO_2 compared to pipelines.
- Due to fuel, maintenance, and driver costs, trucking becomes expensive over time.
- Western Macedonia's mountainous terrain might make road transportation more challenging, especially during winter.

However, transport by trucks might be used as a secondary option for pilot projects or during the initial stages of CO_2 capture, when the captured volumes are small, or as a temporary solution while pipelines are being constructed.

West Macedonia has rail infrastructure, which could be adapted for transporting CO_2 in special tanker cars, similar to those used for transporting other gases. However, this option is likely less attractive for several reasons:

- Rail routes would need to be adapted for CO_2 transportation, and not all emitters and storage sites are located close to railway lines.
- The logistics of transferring CO_2 from emitters to rail cars, and then from rail stations to storage sites, can add complexity and cost.
- Rail could be an option for smaller-scale projects or as an alternative to trucking, but would likely require a multi-modal approach (e.g., rail + truck).

A hybrid system could be an optimal solution, particularly if pipelines are built in phases:

- For Agios Dimitrios, which is closer to Pentalofos, a pipeline could be prioritized.
- For Ptolemaida V, a hybrid approach could involve initial transport by trucks or rail transportation to an intermediate facility, then later switching to a pipeline for longer-term storage when demand for CO_2 capture increases.

This approach allows flexibility and quicker project start-up while spreading the capital costs of pipeline construction over time (Figure 5.26).

- The shorter distance is from Agios Dimitrios to Pentalofos (~50 km), making a pipeline the most practical and efficient choice.
- The longer distance is from Ptolemaida V to Eptachori (~80–100 km), but a pipeline is still preferable for long-term, large-volume storage.

During the construction phase or as a backup, transport by truck could be used for smaller, initial volumes of captured CO_2. However, pipelines should be the ultimate goal for handling continuous and large-scale CO_2 transport, given their ability to handle high volumes and provide a more permanent solution.

5.5.2 Techno-economic description (actions, schedule and costs)

To estimate the total cost of the pipeline transportation system for CO_2 from Agios Dimitrios and Ptolemaida V to the storage sites under Pentalofos and Eptachori, the cost of key components has to be estimated. Cost estimates for CO_2 pipelines are influenced by factors such as pipeline length, diameter, terrain, and installation costs[18]. Below is a rough estimate using typical industry data.

Key Factors for Pipeline Cost Estimation:

- Pipeline Length
- Agios Dimitrios → Pentalofos: Approx. 50–60 km (Figure 5.26).
- Ptolemaida V → Eptachori: Approx. 80–100 km.
- Pipeline Diameter
- Compression Stations
- Permitting, land acquisition, environmental assessments, and contingency.

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[18] Global CCS Institute, Global Status of CCS-Targeting climate change. 2019

Typical CO_2 pipelines are between 12–16 inches [19] in diameter, depending on the volume of CO_2 transported. Given that Agios Dimitrios and Ptolemaida V are large coal power plants, a 14-inch [20] pipeline is a reasonable assumption for this project.

The cost of CO_2 pipelines varies, but typical estimates are between €500,000–€1 million per kilometer for onshore pipelines, depending on the terrain. Since West Macedonia has some hilly areas but is not extreme in terms of elevation, we can assume an average cost of €800,000 per km (Table 5.20) [21].

Compression stations are needed to maintain the pressure of CO_2 along the pipeline. The cost of a compression station varies, but a typical station costs around €5–€10 million, depending on capacity. One or two stations may be needed along each route [22].

Permitting, land acquisition, environmental assessments, and contingency costs typically add about 20–30% to the total project cost [14].

Table 5.20. Estimated Pipeline cost

Pipeline route	Length (km)	Pipeline Cost (€M)	Compression Stations (€M)	Total Cost (including 25% additional costs) (€M)
Agios Dimitrios Pentalofos	50-60	40-48	5-10	56-73
Ptolemaida - Eptachori	80-100	64-80		86-113
Overall Cost (€M)				**142-186**

This estimate gives a rough idea of the potential cost for constructing the pipelines. However, actual costs could vary based on specific project requirements, regional factors (like permitting and terrain challenges), and inflation. Additionally, if there are existing pipelines or other infrastructure that can be repurposed, costs could be reduced.

In Greece, the natural gas network is managed by the Hellenic Gas Transmission System Operator (DESFA), which operates the main high-pressure natural gas pipelines. Key pipelines pass through Western Macedonia, with the region having gained more access to natural gas infrastructure in recent years. High-pressure natural gas pipelines run through the region, connecting the northern and central parts of Greece. The Trans Adriatic Pipeline (TAP) also passes nearby, but that is an international gas pipeline transporting natural gas from the Caspian region to Europe. The Western Macedonia Natural Gas Network Expansion project has been underway to supply cities such as Kozani, Ptolemaida, and others. These are medium-pressure pipelines used for local gas distribution. However, the existing pipelines are primarily built for natural gas transport, and their use for CO_2 would require modifications.

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[19] Global CCS Institute, The Global Status of CCS-Summary report. 2016.

[20] U.S Department of Energy, A Review of the CO2 Pipeline Infrastructure in the U.S., Energy Sector Planning and Analysis (ESPA), Editor. 2015

[21] IEA, Carbon Capture and Storage 2015, IEA, Editor. 2015: Paris

[22] IEAGHG, CO2 Pipeline Infrastructure, T.G.C. Institute, Editor. 2013

Repurposing existing natural gas pipelines for CO_2 transport is possible in certain circumstances, but several technical, regulatory, and economic considerations should be addressed. Pipelines designed for natural gas must be assessed for their suitability to handle CO_2.

Natural gas pipelines operate at different pressures than what is typically required for CO_2. For CO_2 transport, pressures must be maintained above the critical point (73.8 bar for supercritical CO_2) to ensure efficient flow. Pipelines would need to be rated for this pressure. Existing gas pipelines might require retrofitting with additional compression stations and safety systems to handle CO_2. These upgrades would need to ensure the pipeline can withstand CO_2's specific flow and pressure conditions.

The repurposing of natural gas pipelines for CO_2 transport would require approval from both Greek authorities and the pipeline operator (DESFA). CO_2 transport is subject to different regulatory frameworks, and new permits would be needed. CO_2 leakage can pose environmental and safety risks, especially in densely populated areas or near water sources [23]. The retrofitted pipeline must meet strict safety standards to prevent leaks.

5.5.3 Economic results and prioritization

The economic viability of the CCUS project in West Macedonia relies on multiple factors, including the cost of CO_2 capture, transportation, and storage, as well as potential revenue streams from the **utilization of captured CO_2** in local industries. To ensure an effective and sustainable project, a detailed economic analysis should prioritize cost reduction, efficient resource allocation, and value generation.

5.5.3.1 Economic Results

The cost of **capturing CO_2** from Ptolemaida V power plant is expected to be the largest expense in the project, should the plant remain operational. Typical CO_2 capture costs range from **€30–€70 per ton**, depending on the technology and the source of emissions. Capture costs may be at the higher end of this spectrum due to the high carbon intensity of lignite. Assuming an annual capture target of **5 million tons of CO_2**, the total annual capture costs could range between **€150 million and €350 million**.

Transportation costs also form a significant part of the budget, especially if new pipelines are required. Based on previous estimates, the transportation infrastructure (pipelines from Agios Dimitrios and Ptolemaida V to storage locations in Pentalofos and Eptachori) would cost between **€142 million and €186 million**. Spread over 20-30 years of operation, the annualized cost of transportation could range from **€5 million to €10 million per year**, depending on financing structures.

Storage costs in the Mesohellenic Basin are generally lower than transportation and capture but still require investment in well-drilling, monitoring, and regulatory compliance. Costs of **€10–€20 per ton** are typical for geological storage projects, adding approximately **€50 million to €100 million per year** for the expected capture volume.

A preliminary Class 5 Estimate was conducted based on the assumption that 90 Mt of capacity could potentially be identified and proven viable in the Mesohellenic region. This figure should remain an assumption solely for the purpose of running economic models and cannot be considered a reliable estimate for the region's carbon storage capacity. All figures and costs are highly tentative, based on a Class 5 Estimate, and will require further refinement as the project progresses. (Table 5.21)

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[23] Global CCS Institute, Building our way to net-zero: Carbon dioxide pipelines in the United States. 2024.

Table 5.21: Outline of costs, capacities and project details regarding the development of the CO_2 storage in the MHB

Category	Details	Value	Unit
Storage Capacity		90	Mtonnes
CAPEX		301	M$
Inflation Index		2.20%	
Currency Exchange		0.9041	USD/Euro
Contingency		15%	
Seismic Survey	Length	70	km
	Width	30	km
	Line Buffer	2	km
	Number of Seismic Survey Lines (Y axis)	15	
	Total Length (Y axis)	1050	km
	Number of Seismic Survey Lines (X axis)	35	
	Total Length (X axis)	1050	km
	Survey Area	2100	km^2
	Assumed Median Cost per Linear km	10,000	Euro/km
	Seismic Survey 2D Cost	21	Meuro
	Days/km^2	0.0840	days/km^2
	Survey Time Duration	176	days
	Survey Time Duration	0.48	year
Wells	Base Reservoir Depth	3000	m
	Medium Depth Well Cost	4000	Euro/m
	Well Cost	12	Meuro
	Mobilization/Demobilization	2.4	Meuro
	Total Cost per Well	14.4	Meuro
	Number of Wells (1Mtpa/Well Assumed)	3	
	Total Cost for Wells	43.2	Meuro
OPEX Structure (% CAPEX)	Social Engagement (Annual)	2.0%	
	Administrative Cost (Annual)	1.0%	
	OPEX (Annual)	10.0%	
Reference Year		2021	
Project Year		2025	
Critical Activities Cost	Seismic Processing Cost	3.15	Meuro
	Interpretation & Well Location Cost	2.1	Meuro
	Environmental and MOB	6.48	Meuro
	Site Characterization	9.6	Meuro
	Engineering, Procurement & Construction	175	Meuro
	Storage Permit Application & Approval	1.5	Meuro

The development of the storage capacity is projected at 90Mt, with a CAPEX to mature capacity of 301 million Euros and a contingency allocation of 15%. The financial plan incorporates an inflation index of 2.20% and a currency exchange rate of 0.9041 USD/Euro. Below is a summary that outlines the key cost projections and operational details for seismic surveying, well construction and other critical project activities, ensuring financial and operational readiness for the project by 2025.

Seismic Survey Details:

- The seismic survey will cover a 2100 km² area, with survey dimensions of 70 km in length and 30 km in width, with a 2km line buffer
- The total length for both the Y and X axes of the seismic survey grid will be 1050 km.
- The cost for seismic survey is projected at 21 million Euros, with a median cost of 10,000 Euro/km.
- The survey will take approximately 176 days (~0.48 years), requiring 0.0840 days/km² of survey time.

The downtime calculations for the project, accounting for a 20% buffer, vary based on line spacing:

- For 1 km line spacing, downtime is estimated at 0.17 days/km².
- For 2 km line spacing, downtime is estimated at 0.084 days/km².

These values indicate how much time needs to be allocated per square kilometre depending on the spacing of the seismic survey lines.

Well Construction:

- The base reservoir depth (considering Pentalophos Formation) is 3000 meters.
- Medium depth wells (2-3.5km) will cost 4000 Euro/m, with each well costing approximately 12 million Euros, and an additional 2.4 million Euros for mobilization/demobilization.
- A total of 3 wells will be drilled, bringing the total cost to 43.2 million Euros.

OPEX Structure:

- Social engagement costs are estimated at 2% annually.
- Administrative costs will be 1% annually.
- The overall OPEX is projected at 10% annually.

Critical Activities:

- Processing costs are estimated at 3.15 million Euros.
- Interpretation and well location costs amount to 2.1 million Euros.
- Environmental and mobilization costs are projected at 6.48 million Euros.
- Site characterization will cost 9.6 million Euros.
- Engineering, procurement, and construction costs are expected to reach 175 million Euros.
- Storage permit application and approval will cost 1.5 million Euros.

A 3 Mtpa injection for 30 years was assumed with CO_2 price scenario low (75 Euro/tonnes) with 10% discount rate, NPV of the project is 991 million Euros.

To offset these expenses, **CO_2 utilization** in local industries presents an opportunity to generate revenue. Potential uses for CO_2 in enhanced oil recovery (EOR), **cement curing**, and the production of carbonated beverages or other chemical processes could provide a market for some of the captured CO_2. Revenue from these applications may vary, but sales of captured CO_2 typically range from **€15 to €50 per ton**, depending on the market and the industry. If **10-20% of the captured CO_2** (500,000 to 1 million tons per year) is sold for industrial uses, the project could generate annual revenues of **€7.5 million to €50 million**, significantly improving its economic outlook.

5.5.3.2 Prioritisation of Project Components

Given the economic results, it is crucial to prioritize certain aspects of the project to maximize cost efficiency and value generation:

1. **Capture Efficiency**: Priority should be given to optimizing the CO_2 capture process at both plants. Investment in the latest carbon capture technology could reduce long-term operational costs, making it more feasible to capture higher volumes of CO_2. Capturing CO_2 efficiently at the source also ensures the viability of the downstream processes (transport and storage).
2. **Utilization Opportunities**: Priority should also be placed on **local CO_2 utilization** to create a **circular economy** for carbon. Developing partnerships with industries that can use CO_2, such as the **cement** or **carbonated beverage industry**, should be a focus early in the project. By integrating these industries into the CO_2 supply chain, the region can generate revenue while reducing overall transportation and storage needs.
3. **Pipeline Infrastructure**: If utilization opportunities are limited or underdeveloped initially, the project should prioritize the construction of **CO_2 pipelines** to storage sites. Given the high cost of building new pipelines, a strategic decision should be made to either construct separate pipelines from the emitter or create a **shared pipeline network** from the emitter and CO_2 hub to reduce capital expenditure.
4. **Phased Storage Development**: As storage costs are a smaller percentage of the total budget, it is possible to **phase the development of storage sites**. The project could begin by focusing on one storage location, such as **Pentalofos**, which may be closer and easier to develop, before expanding to other locations like **Eptachori** as CO_2 capture volumes increase.

By carefully prioritizing capture efficiency, utilization opportunities, and strategic infrastructure development, the Western Macedonia CCUS project can reduce costs, generate additional revenue streams, and ensure long-term economic viability.

5.5.4 Final development selection

In the final phase of developing the CO_2 Capture, Utilization, and Storage (CCUS) project in Western Macedonia, key decisions must be made to ensure the project's long-term viability and alignment with both economic and environmental goals. The selection of the final development plan should focus on integrating CO_2 capture, efficient transportation, and storage, while also maximizing opportunities for CO_2 utilization within local industries.

5.5.4.1 Integrated Infrastructure and Phasing Approach

Given the project's complexity and scale, a phased strategy is advised for the final stages. This enables incremental scaling of CO_2 capture and transportation, spreading out capital expenditures over time and adjusting changing technological and market conditions. The first phase should focus on optimizing capturing facilities at the Agios Dimitrios and Ptolemaida V power plants. Implementing capture systems at both facilities at the same time can result in economies of scale, but initial efforts should focus on smaller storage volumes at the most accessible storage facility, which is likely Pentalofos. As capture capacity grows, transportation infrastructure, like as pipelines, can be developed to reach the second storage location in Eptachori.

A **combined CO_2 pipeline network** for both power plants is an efficient option that eliminates the need for separate infrastructure and lowers upfront capital expenses. The pipeline design should consider potential future expansions for greater capture volumes and more CO_2 emitters joining the network. Furthermore, compression stations should be strategically located throughout the pipeline to guarantee proper pressure management, with the option of adding additional stations as the project grows.

5.5.4.2 Utilization and Market Development

To increase the project's financial feasibility, CO_2 utilization opportunities should be prioritized. Early identification of local industries that can use captured CO_2 can reduce shipping and storage costs. The project aims to integrate the local CO_2 economy by involving industries such as cement, concrete curing, and chemical production. A portion of captured CO_2 should be distributed to these industries, establishing a direct revenue stream while minimizing the total volume transferred to storage.

Formalizing ties with local firms throughout the final development stage ensures a stable market for CO_2. These collaborations not only improve the project's economics, but also establish Western Macedonia as a hub for long-term industrial growth, thereby facilitating the transition to a low-carbon economy. By developing research and development partnerships, the region might explore more novel uses of CO_2, such as synthetic fuels or improved materials. This would open up new paths for CO_2 consumption.

5.5.4.3 Long-Term Storage Security

The final development selection must ensure **secure and scalable storage**. Given the geological characteristics of the **Mesohellenic Basin**, it is essential to conduct thorough assessments of both Pentalofos and Eptachori as potential long-term storage sites. Initial phases should focus on **Pentalofos** due to its relative proximity to the power plants and potentially lower development costs. As the project progresses, **Eptachori** can serve as an additional storage reservoir, ensuring sufficient capacity to store all captured CO_2 over the project’s lifespan.

Monitoring and verification systems must be established from the outset to ensure the integrity of the storage sites. This involves continuous tracking of injected CO_2, pressure monitoring, and regular safety assessments to prevent leakage and ensure compliance with **regulatory frameworks**. These measures will provide confidence in the project’s environmental impact, while also meeting national and EU regulations for CO_2 storage.

The final development selection should balance the immediate technical, economic, and regulatory needs with the long-term vision of creating a sustainable CCUS system in Western Macedonia. By adopting a phased approach, integrating local CO_2 utilization opportunities, and ensuring secure storage, the project can not only reduce greenhouse gas emissions but also contribute to the region’s economic development and industrial innovation.

6. Conclusions

6.1 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.

At this preliminary stage, the models are only used to estimate the CAPEX requirements to rank the different scenarios.

Considering the pipeline and truck transport chain, the CAPEX of the two transport modes shows a clear difference between transport by truck (25.7 MEUR) and pipeline transport (15.7 M EUR).

In addition, combined with the transport mode there are other 2 scenarios considered: off-site injection and on-site injection. The latter being less CAPEX intensive because no pipeline is required even though drilling length might be significantly different due to well deviation to limit interferences with disposal operations at the emission site. The disposal well located on-site is open hole over the target formation and is used when the plant operates. Thus, interferences are expected between the brine disposal and CO_2 injection which may be detrimental to both operations. This imply an injection point away from the disposal well.

The large deviations of the well to limit interferences with the disposal well operations and the industrial surface installations which limit the monitoring capabilities would favour off-site injection scenarios which will be retained for detailed dimensioning studies which includes the following designs and cost estimates:

- Compression
- Pipeline
- Injection well
- Monitoring & Verification

The preliminary schedule includes the uncertainties on the various administrative and technical tasks:

- Pipeline: preliminary studies, detailed routing, detailed studies, administrative file for permitting, administrative authorization investigations, long-lead Items, land access negotiations, construction
- Compression: detailed studies, long-lead Items, construction
- Well: detailed studies, drilling permit authorization, long-lead Items, drilling and completion

Given the various delays above, all administrative authorization would be obtained in month 37 (beginning of year 4) at the earliest. The start of CO_2 injection would be in month 62 (beginning of year 6) at the earliest while the base line monitoring might start in year 5.

6.2 Lusitanian Basin (Portugal)

The baseline case for the Lusitanian Basin CCS project comprehends two injection phases: Phase I – a pilot-scale injection of up to 270 kt CO2 for 3 years – followed by Phase II – commercial upscaling injection of up to 0.5 Mt/year during a 30-year timespan.

The foreseen scenarios consider

1) an intermittent injection associated with train transport between local CO_2 sources and storage sites.
2) continuous injection from the Figueira da Foz port with offshore pipeline transport (23 km).

For the pilot phase, CO_2 sources are assumed to be from the closer points, 50 to 80 km from the storage site. It is also considered the possibility of a limited amount of 60-90 kt CO_2 per year and CO_2 transport by train & ship as the best option, given the flexibility, cost efficiency, and the relatively low infrastructural impact. Avoiding pipeline transport in the pilot phase would also dramatically decrease

CAPEX costs. Shipping transport to the storage site would be enough to ensure continuous injection and avoid the need for permanent infrastructure in the early project stages.

The injection pilot phase is designed to achieve three primary objectives: to characterise the offshore reservoir, test the CO_2 injection conditions, and assess the quality of the caprock to ensure secure long-term storage. The pilot is designed to inject CO_2 at a rate of 90 kt per year, with a total injection volume of 270 kt over three years.

The choice of transport mode depends on the project phases. Among the scenarios considered, train transport and shipping are proposed only in the pilot Phase I (fast-track development at minimal cost to prove technical feasibility). The commercial injection (Phase II) scenario prioritises offshore pipeline transport due to its operational and logistical advantages.

The start of pilot CO_2 injection would be in year 5, followed by 4D seismic acquisition by year 7. This would allow a FID of the commercial upscaling by the end of year 7, in order to start developing the Phase II injection with the pipeline development and commercial injection by year 10.

6.3 Ebro Basin (Spain)

Ebro basin scenarios are based on a pre-commercial phase (pilot scale) and commercial phase with full life cycle evaluation under common economic frame and approach described earlier. The evaluation includes the storage site operation, that is, no capture nor transport is included. It is assumed CO_2 stream impurities compatible with Lopín storage site and no limitations due to CO_2 quality. Selected scenarios have been described, economically evaluated for the full life cycle, and economic parameters compared in order to selected the optimum option.

These are the three selected scenarios to be evaluated:

- **Minimum cost**: proposed development based on minimising investment and operational costs (OPEX).
- **First-of-its-kind**: following current proposals for ongoing developments, which main priority is to build social thrust, validate best practices, and dimension MMV activities for an exhaustive control.
- **Green development**: similar to the previous one but ensuring a green energy supply and optimising energy consumption.

The work carried out on the dynamic modelling has been focused on the base case scenario (assuming compartmentalisation). For a vertical well design, it is given a maximum storage capacity of CO_2 over a period of 30 years safely injected at optimal injection rates of **2.14 million tonnes** (approx. 70 kt/yr). However, with the objective of evaluating a commercial case, it is also considered the case of not compartmentalisation, with an estimated volumetric capacity calculated from this model of **23 Mt**, and a maximum injection rate of 0.5 Mt/yr per well.

The project's phases include, in general:

- Permit-granting-process (12 months)
- G&G activities (12 months)
- Exploration well design (12 months), assuming G&G positive results.
- Reused exploration well followed by completion.

- Initial injection test of 0.03 Mt/yr during 3 years; 0.5 Mt/yr thereafter.
- Injection facilities design and building.
- MMV: Monitoring well (out of area of plume expansion) and fibre optic in the injector. Seismic surveying every 6 years.
- Abandon when maximum capacity is reached.

The economic evaluation has tried to identify the better strategy to apply considering current information available. The main uncertainty is the estimates capacity and existing or not compartmentalisation limiting maximum injection rate and total volume. Based on it, the evaluation shows economic results for NPV (9%, 2025) for the 2 Mt, 4 Mt and 23 Mt cases, and identified that NPV is highly dependent on storage prices and breakeven. Based on it, the Minimum investment scenario is the most robust case for the different prices.

Based on cash-flow, cash-out and flexibility, the Minimum Investment case present lower initial investment and faster than the other two scenarios recuperation to a positive balance. At long term, the Green Development show better income results and positive parameters.

The Minimum Investment scenario is, therefore, the preferred scenario. It has the following advantages over the other two scenarios:

- Minimum initial investment adaptable both for low capacities and higher capacities.
- It is the most robust based on breakeven prices.
- Simplified development phases and operations, therefore reducing the project's complexity.
- Lower local impact and easier social acceptance.
- Adaptable to any source including low volume and DAC (direct air capture).

6.4 Upper Silesia Basin (Poland)

The objective of the task was a simplified economic evaluation to have a first overview of the project economics. The life-cycle approach taking into account the pilot phase as well as the commercial phase was considered for economic evaluation to provide important information to policy-makers, scientists, and engineers enabling assessment of the technology. The simplified economic evaluation was performed for the one conceptual scenario, which was identified during a framing session phase conducted previously.

The main assumptions of the scenario were as follows:

Pilot phase

Amount of CO_2	30 kt/y
Transport	road
Tank trucks	4*25 t/d=100 t/d * 300 d = 30 kt/y
Duration	3 years of injection

Commercial phase

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

- Amount of CO_2 300 kt/y
- Transport pipeline
- Duration 25 years of injection

Total amount of CO_2 injected during both phases: 7.59 Mt

Capacity of the storage site 30 Mt

The techno-economic analysis was performed for a 33-year period covering the following phases:

- geological surveys, modelling, preparation of technical documentation and obtaining the necessary administrative decisions: 3 years,
- pilot installation implementation: 2 years,
- pilot installation operation: 3 years,
- commercial installation implementation: 2 years,
- commercial installation operation: 25 years.

In order to assess the economic efficiency of the analysed concept of CO_2 capture, transport and injection into the underground reservoir, the NPV and IRR indices were calculated for three scenarios of forecast prices of CO_2 emission allowances purchase:

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

The obtained results indicate that the investment is economical only when the commercial phase is included in the calculations and in the case of the scenario with the highest prices of CO_2 emission allowances (NPV of 89.81 MEUR and IRR of 14.6%). The pilot phase is not effective for any CO_2 price scenario. But this is in line with expectations - the pilot phase is to demonstrate that CO_2 injection is technically feasible and that a commercial phase can be implemented.

The preliminary schedule includes the pilot phase as well as the commercial phase:

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

6.5 Western Macedonia Basin (Greece)

In summary, the project aims to develop a storage capacity of 90 million tons, with a total capital expenditure (CAPEX) of approximately 301 million Euros, complemented by a 15% contingency allocation. The financial estimates, rooted in 2021 figures, indicate that the project is set to commence in 2025, factoring in a 2.20% inflation rate and a currency exchange rate of 0.9041 USD/Euro.

The seismic survey, covering a substantial 2,100 km^2 area, is projected to cost 21 million Euros and will take around 176 days to complete. The downtime for the seismic survey varies significantly based on line spacing, impacting the overall project timeline. Well construction involves drilling three medium-depth wells at an estimated total cost of 43.2 million Euros, inclusive of mobilization expenses.

Operational expenditures (OPEX) are structured to include social engagement and administrative costs, cumulatively projected at 8% annually. Additionally, critical activities, such as processing, interpretation, environmental assessments, and engineering, procurement, and construction, have been outlined, totalling significant projected costs.

The assumed timeline indicating the project's major stages, leading to the first injection planned for Q1 2033. Overall, this comprehensive financial and operational framework lays the groundwork for ensuring readiness and successful implementation of the project by 2025. A 3 Mtpa injection for 30 years was assumed with CO_2 price scenario low (75 Euro/tonnes) with 10% discount rate, NPV of the project is 991 million Euros.

In addition, a detailed feasibility study should be conducted to assess whether any sections of the existing network can be economically repurposed. However, dedicated new pipelines from Agios Dimitrios and Ptolemaida V to Pentalofos and Eptachori are likely to be a more reliable and cost-efficient solution in the long term, considering the specific needs for large-scale CO_2 transport.

Reducing the costs of CO_2 transportation can be achieved by utilising captured CO_2 in local industries, creating a revenue stream that offsets transportation and storage expenses. In Greece, captured CO_2 could be used in several industrial applications, such as enhanced oil recovery (EOR), producing carbonated products, or in the cement and concrete industry where CO_2 is used to cure concrete and improve its strength [24]. By creating a market for CO_2 within the region, the volume transported to storage sites could be reduced, minimizing the need for long-distance pipelines and compression stations, thereby cutting capital and operational costs.

Moreover, establishing CO_2 utilization hubs at the current infrastructure of Agios Dimitrios and Ptolemaida V power plants could attract new industries that benefit from low-cost, readily available CO_2. This would stimulate regional economic activity while reducing the need to transport all captured CO_2 to distant storage locations. Integrating CO_2 utilization with local industrial demand is a practical way to improve the overall economics of CCUS projects.

While repurposing pipelines might save on construction costs, the retrofitting, upgrading, and regulatory approval processes could still be costly. It is important to weigh whether these costs are lower than building new CO_2-specific pipelines.

There are no known large-diameter natural gas pipelines passing directly through the existing infrastructure of power plant locations (Agios Dimitrios and Ptolemaida V). Most of the natural gas

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[24] The Global Status of CCS: 2020. Available at: Global CCS Institute

infrastructure in the region is for local distribution and would not be suited to high-volume CO_2 transport without significant modification.

The storage locations (Pentalofos and Eptachori) are in the Mesohellenic Basin, further from the current natural gas pipeline routes. If existing pipelines do not align well with these routes, new CO_2 pipelines may be more cost-effective than repurposing gas pipelines.

While technically possible, repurposing existing natural gas pipelines for CO_2 transport in West Macedonia would likely face significant technical and regulatory hurdles. The current natural gas infrastructure is designed for lower pressures and specific routes, and the upgrades necessary for CO_2 transport may make this option less attractive than building new, dedicated CO_2 pipelines.

7. References

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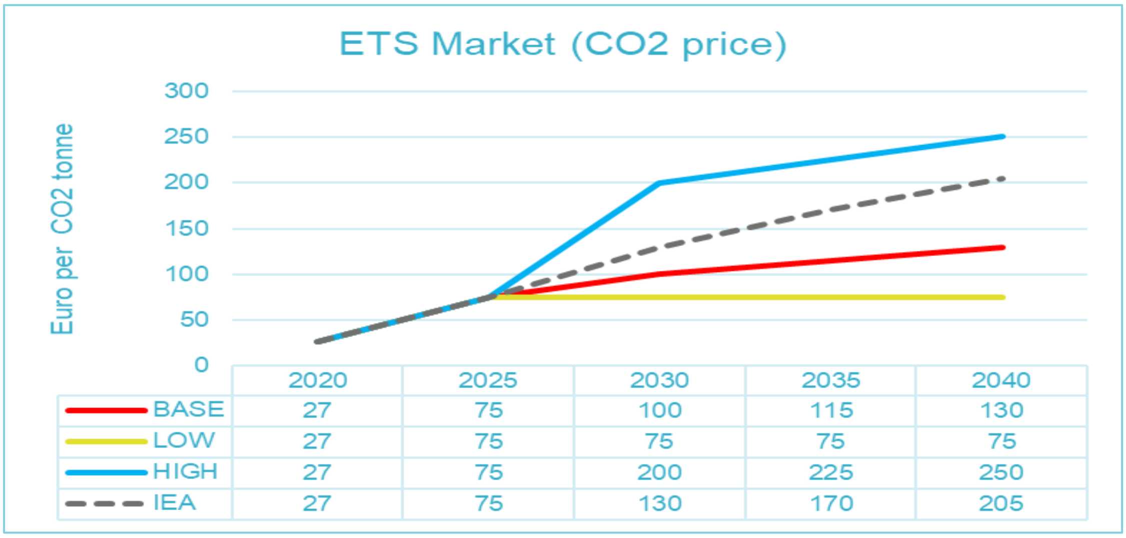
The PilotSTRATEGY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101022664

8. Annex: CO_2 price forecast

To establish a CO_2 pricing forecast, the PilotStrategy team had agreed on some figures that are considered to be neither very optimistic nor very pessimistic.

About the price evolution, it seems there is a general consensus that they will be increasing in the future in the EU; the paces and values are arguable. In some forecasts the increase is somehow linear; in other cases, they are predicted to increase sharply from 2040. It is not the objective of this report to discuss these predictions, so in the following figure there are the figures we have considered (Figure 8.1).



	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 8.1: CO_2 prices evolutions that have been considered in this report.

About the present CO_2 prices in the EU, they can be followed on this web ([https://tradingeconomics.com/commodity/carbon)](https://tradingeconomics.com/commodity/carbon)

Figure 8.2 Carbon price evolution from 2006 (took from tradingeconomics.com)

Several forecast models have been consulted:

- **Global Carbon Market Outlook 2024 | BloombergNEF (bnef.com)**

The Bloomberg website provide the following information about the company:*" Bloomberg is a global leader in business and financial information, delivering trusted data, news, and insights that bring transparency, efficiency, and fairness to markets. The company helps connect influential communities across the global financial ecosystem via reliable technology solutions that enable our customers to make more informed decisions and foster better collaboration."* Specifically, Bloomberg NEF *"provides independent analysis and insight, enabling decision-makers to navigate change in an evolving energy economy."*

In its BNEF blog (https://about.bnef.com/blog/global-carbon-market-outlook-2024/) they have the following forecast:

"California's carbon price is expected to average around $42 per metric ton in 2024 and $46 per ton in 2025, according to BloombergNEF. That's up to $34 per ton in 2023, supported by financial intermediaries. It could reach as high as $93 per ton by the end of the decade. Meanwhile, carbon prices in EU are forecast to average €71 per ton ($76 per ton) this year, down from €85 per ton in 2023. BNEF then projects the bloc's prices will head towards €146 per ton in 2030. Carbon markets offer investors access to a tool that tracks a diverse set of low-carbon technologies. They could also attract investors looking to shield their returns from high interest rates and inflation."

- **Carbon Price Forecast 2030-2050: Assessing Market Stability & Future Challenges | Enerdata**

As stated in its website (https://www.enerdata.net/about-us/): "*Enerdata is an independent research company that specialises in the analysis and forecasting of energy and climate issues. We do this at a variety of different geographic and business / sector levels. Our company is headquartered in Grenoble, France, where we were founded in 1991, and has a subsidiary in Singapore.*

Leveraging our globally recognised databases, business intelligence processes, and prospective models, we assist our clients – which include companies, investors, and public authorities around the world – in designing their policies, strategies, and business plans."

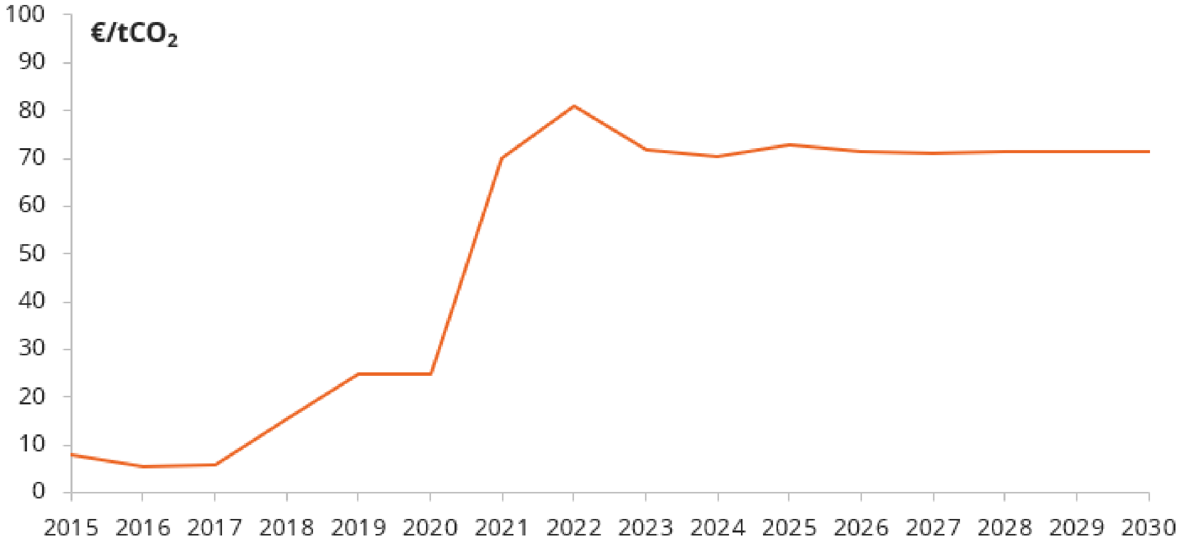
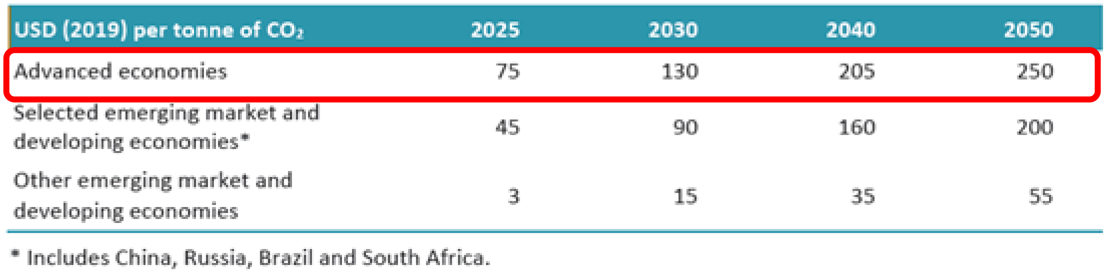


Figure 8.3 The EU ETS carbon price evolution until 2030, source ENERDATA, POLES mode. (https://www.enerdata.net/publications/executive-briefing/carbon-price-projections-eu-ets.html)

- **International Energy Agency (IEA)**

The International Energy Agency was created in 1974 to help co-ordinate a collective response to major disruptions in the supply of oil. Since 2015, the IEA has opened its doors to major emerging countries to expand its global impact, and deepen cooperation in energy security, data and statistics, energy policy analysis, energy efficiency, and the growing use of clean energy technologies. (source: https://www.iea.org/about/mission).



USD (2019) per tonne of CO_2	2025	2030	2040	2050
Advanced economies	75	130	205	250
Selected emerging market and developing economies*	45	90	160	200
Other emerging market and developing economies	3	15	35	55

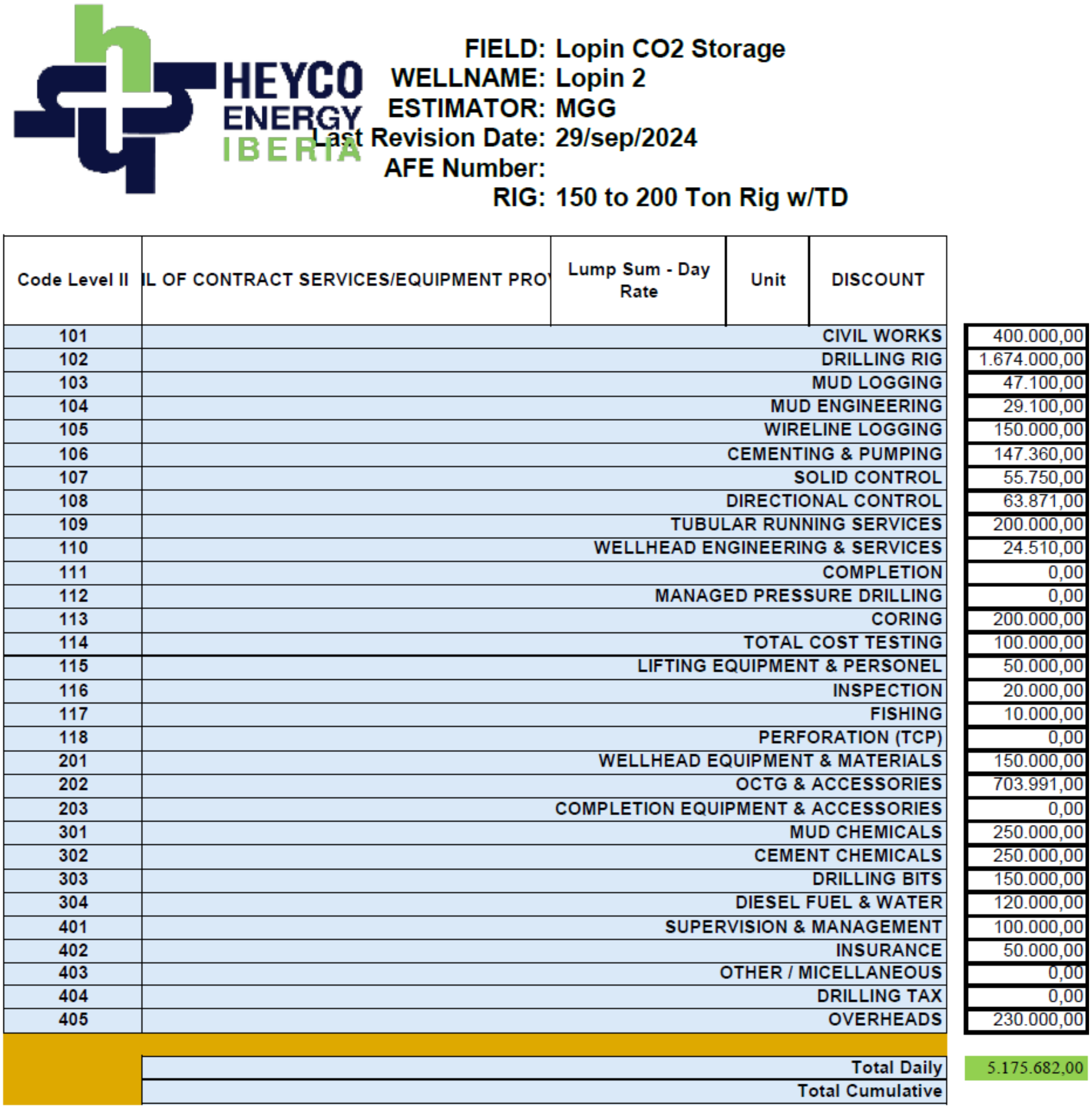
* Includes China, Russia, Brazil and South Africa.

Figure 8.4 Table CO_2 prices for electricity, industry and energy production in the Net Zero pathway from EIA report "Net Zero by 2050: a Roadmap for the Global Energy Sector" (https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf)

9. Annex: Costs sources and references for Ebro Basin evaluation

9.1 Well costs

Based on Viura-2 well drilled onshore in 2024 (La Rioja, Spain). Courtesy of Heyco Energy.



FIELD: Lopin CO2 Storage
WELLNAME: Lopin 2
ESTIMATOR: MGG
Last Revision Date: 29/sep/2024
AFE Number:
RIG: 150 to 200 Ton Rig w/TD

Code Level II	IL OF CONTRACT SERVICES/EQUIPMENT PRO	Lump Sum - Day Rate	Unit	DISCOUNT	
101	CIVIL WORKS				400.000,00
102	DRILLING RIG				1.674.000,00
103	MUD LOGGING				47.100,00
104	MUD ENGINEERING				29.100,00
105	WIRELINE LOGGING				150.000,00
106	CEMENTING & PUMPING				147.360,00
107	SOLID CONTROL				55.750,00
108	DIRECTIONAL CONTROL				63.871,00
109	TUBULAR RUNNING SERVICES				200.000,00
110	WELLHEAD ENGINEERING & SERVICES				24.510,00
111	COMPLETION				0,00
112	MANAGED PRESSURE DRILLING				0,00
113	CORING				200.000,00
114	TOTAL COST TESTING				100.000,00
115	LIFTING EQUIPMENT & PERSONEL				50.000,00
116	INSPECTION				20.000,00
117	FISHING				10.000,00
118	PERFORATION (TCP)				0,00
201	WELLHEAD EQUIPMENT & MATERIALS				150.000,00
202	OCTG & ACCESSORIES				703.991,00
203	COMPLETION EQUIPMENT & ACCESSORIES				0,00
301	MUD CHEMICALS				250.000,00
302	CEMENT CHEMICALS				250.000,00
303	DRILLING BITS				150.000,00
304	DIESEL FUEL & WATER				120.000,00
401	SUPERVISION & MANAGEMENT				100.000,00
402	INSURANCE				50.000,00
403	OTHER / MICELLANEOUS				0,00
404	DRILLING TAX				0,00
405	OVERHEADS				230.000,00
	Total Daily				5.175.682,00
	Total Cumulative				