WP4 -Deliverable 4.3

Final concept description and preliminary consideration by regions.

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2. Executive summary

The objective of the WP4 is to provide and analyse available information on 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.

As it is described in D4.1 *Methodology for alternatives definition, prioritisation, and selection*; D4.2 *Conceptual scenarios definition to enable decision support*, and D4.9 *Economic evaluation of alternatives and priorization results*, each region has defined selected scenarios, reviewed them, and carried out a techno-economic evaluation, selecting the optimum development scenario for each region, i.e., Paris Basin, Lusitania Basin, and Ebro Basin; and, more general approach for Silesia Basin and Macedonia Basin. Those selected developments will be optimized during next months, being the basis for the final investment decision report.

This deliverable describes from a technical point of view the selected scenario for each region as a starting point for the next phase of project definition.

Paris Basin (France):

The French case is based on a pilot-scale with an injector well 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 coming from SMR (steam methane reforming) plant. The plant is also operating a waste-water disposal well (vertical open-hole) located on-site and interferences are expected between the brine disposal and CO_2 injection. To avoid this, the distance between both wells is about 3 km. The connection between capture plant and injector well is done by 3 km pipeline.

At this stage, no specific consideration was carried out for Monitoring and Verification plan of the pilot operations, although it is expected a seismic-sensitive fiber optic cable could be installed in the injection well to enable frequent VSP measurement campaigns.

Lusitanian Basin (Portugal):

The case for the Lusitanian Basin CCS project, comprehends two injection phases: a **pilot-scale injection** of up to 100 kt CO_2 for 5 years, followed by a **commercial upscaling** injection of up to 0.5 Mt/year during a 30-year timespan. For the pilot phase, CO_2 sources are assumed to be from the closer emitters (up to 80 km), with a limited amount of 60-90 kt CO_2 per year transported by train to a hub and then, by ship, avoiding pipeline transport during pilot. Assuming result from the pilot are well enough, an upgrade for the commercial scale is done including an offshore pipeline connecting with the storage site.

The start of pilot CO_2 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 (Final Investment Decision) 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.

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Ebro Basin (Spain):

Ebro basin selected scenario is based on a pre-commercial phase (pilot scale) and commercial phase with full life cycle. There is not selected emitter although few potential ones are identified in the proximity (<60km). It is assumed CO_2 stream impurities compatible with Lopín storage site and no limitations due to CO_2 quality.

The selected development is a flexible one based on the current uncertainty of the potential storage volume, in a range between 2 Mt and 26 Mt. It is proposed an initial phase of 1 year (pilot phase) with a well, injecting 0.03 Mt/year, and a commercial phase with 0.5 Mt/year thereafter until reach maximum estimated capacity. The exploration phase has been defined considering G&G activities and an exploration well, reused as injector. Assuming results from exploration confirm storage capacity for commercial development, new injector well would be drilled as needed.

MMV preliminary plan has been included, combining a monitoring well (out of area of plume expansion) and fibre optic in the injector.

Upper Silesia Basin (Poland):

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. Regarding transport, during pilot phase construction of pipeline wouldn't be reasonable, road transport is expected and sufficient. However, implementation of CCUS technology in larger scale requires construction of the pipeline. Three perspectives were considered during planning of a CCS installation in Upper Silesia:

- **Within 5 years** – CCS pilot on a scale 100,000 tons of CO_2/3 years.
- **Within 10 years** – Proving the feasibility and investors attraction.
- **Within 50 years** – monitoring after closure.

Macedonia Basin (Greece):

A phased strategy it is recommended. 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 optimising capturing facilities at the Agios Dimitrios and Ptolemaida V power plants. 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.

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3. Introduction

The objective of the WP4 is to provide and analyse available information on 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. This task is fed with inputs from other work packages; therefore, there is a retrofitting process that may push modifications from the first approaches to the more updated final options.

As it is described in the deliverables D4.1 *Methodology for alternatives definition, prioritisation, and selection*; D4.2 *Conceptual scenarios definition to enable decision support*, and D4.9 *Economic evaluation of alternatives and priorization results,* each region has defined regional scenarios, reviewed them, and carried out a techno-economic evaluation, selecting the optimum development scenario for each region, i.e., Paris Basin, Lusitania Basin, and Ebro Basin; and, with general approach, for Silesia Basin and Macedonia Basin. Those selected developments will be optimized during next months, being the basis for the final investment decision report.

This deliverable describes from a technical point of view the selected scenario for each region as a starting point for the next phase of project definition.

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 and, when it is applicable, upgrade to commercial scale, and at level of knowledge expected at this stage.

4. Final concept description by regions

4.1 Paris Basin (France)

4.1.1 Final scenario overview

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 CO_2 source plant. The plant is also operating a waste-water disposal well (vertical open-hole).

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 the dynamic modelling (D3.3, Chassagne, 2024), the extension of the CO_2 plume is about 700 m around the well implying an injection point further away to avoid pressure interferences. Consequently, the down-hole injection locations for the CO_2 is finally decided to be distant by about 3 km assuming worst-case scenario from the deliverable D3.3 (Chassagne, 2024).

The connection between capture plant and injector well is done by 3 km pipeline based on the better economic evaluation described on D4.2. in comparison with truck.

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At this stage no specific consideration were focussed on the Monitoring and Verification of the pilot operations. However, as it is expected a migration of CO_2 plume lower than 1 km, a seismic-sensitive fiber optic cable could be installed in the injection well to enable frequent VSP measurement campaigns. The monitoring plan shall be proposed by WP5.

4.1.2 Storage

4.1.2.1 The injection well

The condition (pressure, temperature) at the target formation -Oolithe Blanche in the Seine-et-Marne area from the Île-de-France- defines the requirements for the upstream equipment (well head, pipeline and required compression) to meet the expected injection conditions. The Table 4.1 shows the stratigraphic column at vertically from the bottom hole location (ground level = 108 mMSL) of injection well, PSTY01:

Table 4.1 Expected lithostratigraphic column at the bottom hole location for PSTY-01

		Top Depth (TVDSS)	Top Depth (TVD)	Lithological description	Reservoir / Caprock	Fluids
TERTIAIRE	**Oligocene**			Shales, some limestones		
	Eocene			Mudstone, sands, clays		
CRETACE	**Senonien Turonien**	28,9	136,9	Chalks with some cherts		
	Cenomanien	602,3	710,3	Limestones		
	Albien argileux (Argiles du Gault)	686,3	794,3	Claystones, sandy		
	Albien sableux - Sables verts	729,3	837,3	Sands	Albien	Water
	Albo aptien	773,7	881,7	Sands and clays		
	Barremien	762,3	870,3	Claystones, sandy, silt, sandstones		
	Neocomien			Claystones, sandy, sandstones and sands		
JURASSIQUE	**Purbeckien**	1025,7	1133,7	Limestones mudstone. Dolomites, anhydrites		
	Portlandien	1060,7	1168,7	Limestones mudstones, some shales		
	Kimmeridgien	1181,8	1289,8	Shales, silty		
	Oxfordien supérieur - Lusitanien	1346,8	1454,8	Limestones mudstone, silty		
	Oxfordien inférieur	1617,0	1725,0	Shales, silt, pyrite, some limestones.	Caprock 2	
DOGGER	**Callovien supérieur CA28**	1724,2	1832,2	Shales and clays chalky	Caprock 1	
	Callovien inférieur - Dalle nacrée - Comblanchien = CA26	1734,1	1842,1	Limestone, slight clay		Water
	Bathonien - Oolithe Blanche = SB_Comb	1765,2	1873,2	Limestones	**Oolithe blanche**	Water
	Bathonien - Bt10	1865,7	1973,7	Limestones		Water
	Bajocien = BJ1	1925,9	2033,9	Shales, silt. Limestones		
LIAS	**Aalenien**			Shales, clay, chalky clays		
	Toarcien	1976,9	2084,9			
	Lias moyen à inférieur	2074,1	2182,1			
TRIAS	**Rhetien**			Clay sandstones		
	Keuper (Grès de Chaunoy et Donnemarie)			Clay sandstones		

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The target storage formation, Oolithe Blanche, is overlain by a tighter carbonated reservoir (Comblanchian) and two cap-rock formations (see Deliverable D2.7 [Wilkinson, 2023] for more details). The main characteristics of the injection well are summarized in
Table 4.2

Table 4.2 Main characteristics of PSTY01 injection well

Item	Description
Drilling Location	Seine-et-Marne
Well name	PSTY-01
Well type	CO_2 (injector)
Well classifications	Deviated S-shape
Target Formation(s)	Oolithe blanche
Formation type	carbonate
Grid Coordinate System	RGF93 – Lambert 93
Ground Level (m MSL)	110
Well material	EPA directing[1] all Class VI Projects to used 22Cr minimum for all wells (Injection and monitoring) in the injection zones for Class VI.
Well TD	1966 m TVDSS / 2083 m TVD (Bajocien)
Well design lifetime (year)	30

Based upon the geological and dynamic constraints, a preliminary design of the well is illustrated in Figure 4.1.

4.1.2.2 Conditions at the injection well

No information is available regarding the pore pressure and temperature profiles along the well. The fracture pressure estimates are obtained from the deliverable D3.3 (Chassagne, 2024). The expected operation conditions in the injection well are summarised in Table 4.3. The main design constraints are the maximum injection pressure, between 19 and 21 MPa, and formation temperature (about 60°C) which will control the well-head conditions to avoid both a two-phase flow within the injection tubing and a significant pressure expansion (Joule-Thomson effect) between the wellbore and the formation.

Table 4.3 PSTY-01 operating envelope for the selected injection scenario (PilotStrategy deliverables D4.2 [Canteli et al. 2024] and D3.3 [Chassagne, 2024])

Item	Description
Initial storage pressure (bar @ 1750 mTVDSS)	171.5
Initial storage temperature (°C @ 1750 mTVDSS)	60
Operational flow rate (kt/y)	300
Cumulative injection (kt)	100
Injection duration (months)	4
Bottom Hole Injection Temperature (°C)	40
Bottom Hole Pressure (bar) P10/P50/P90	212 / 201 / 196

[1] ADM carbon sequestration project violated Safe Drinking Water Act, per EPA (capitolnewsillinois.com)

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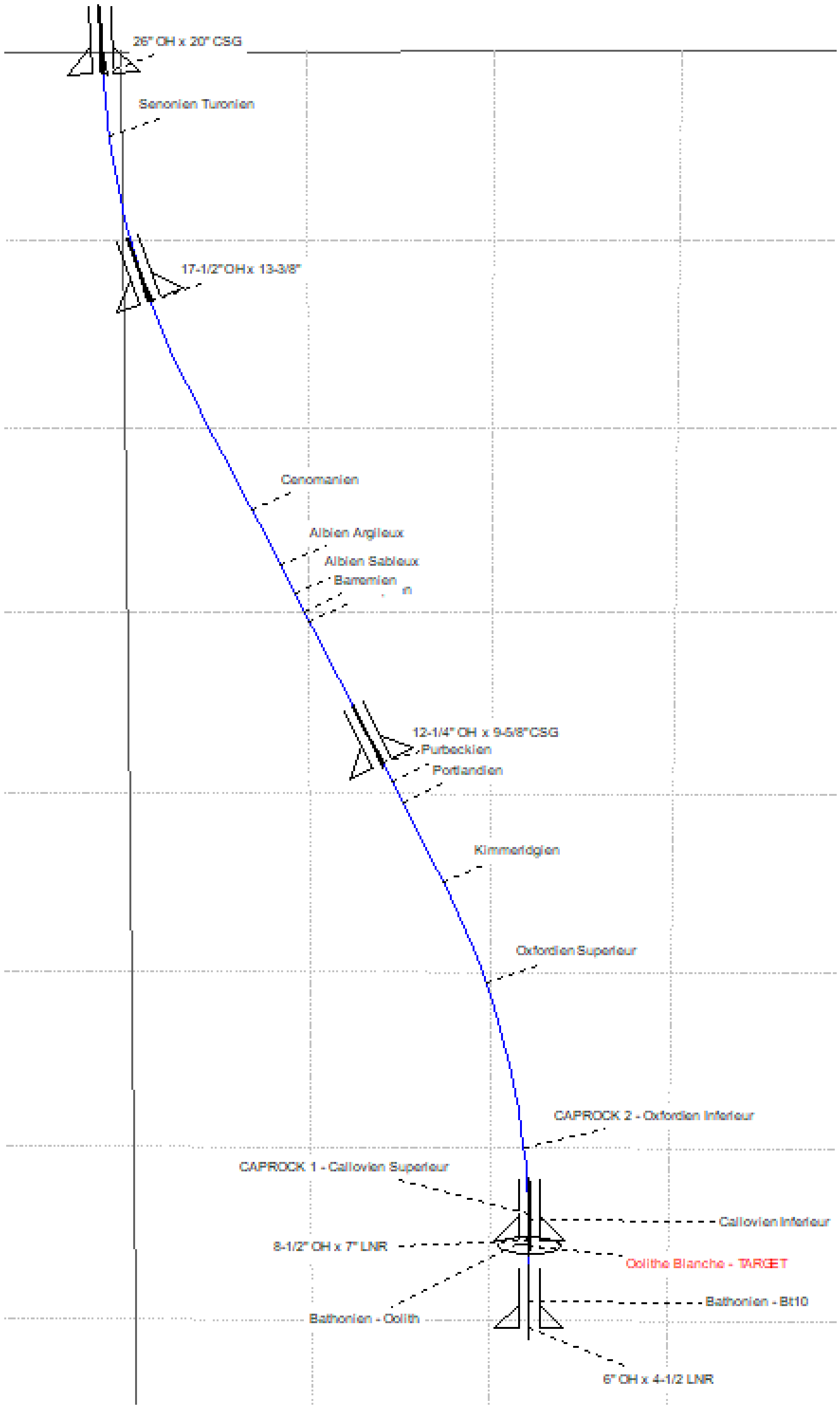

Figure 4.1 Preliminary well design showing the different drilling section and expected formation from Table 4.1.

From the deliverable D3.3 (Chassagne, 2024), the pilot injection will target a 40-meter vertical interval above the Bt12 horizon as shown in Figure 4.2.

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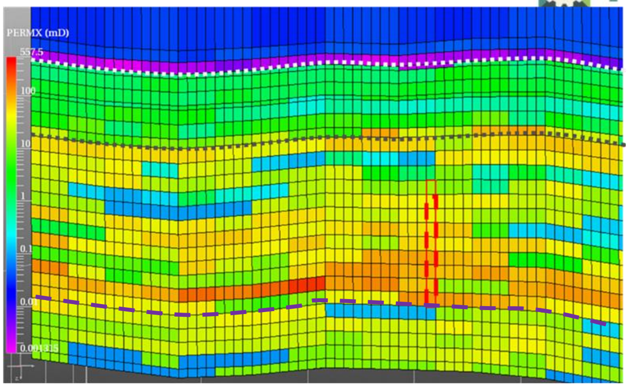

Figure 4.2 From top to bottom: illustration of the well location (red dashed rectangle) in the P50_BC model. Permeability field in XY View (Y normal) with a vertical exaggeration. White dotted line: limit between COX and Dogger aquifer. Black dotted line: limit between Oolithe Blanche and Comblanchien formation. 40m-length perforation is considered, beginning from the Bt-12 Horizon (bottom perforation- purple dashed line) within the Oolithe Blanche Formation. Scale: cells' size is approx. 62.5x62.5x5m. (from figure 3.23 from D3.3)

To meet the pressure requirements from WP2, a preliminary estimate of the pressure drop within the well was carried out using Prosper™ v17.5 from Petex[2] to model the multiphase flow pressure drop within the well. This recent version of the software includes the equation of state from NIST for pure CO_2. Assuming average thermal properties for the different formation above the storage formation [Dentzer *et al*., 2018], the well-head pressure is about 10MPa

4.1.2.3 Offset wells

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. Based upon the results of the deliverable D3.3 (Chassagne, 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 (D3.3), the CO_2 injection and brine disposal should be even further away as illustrated in Figure 4.3:

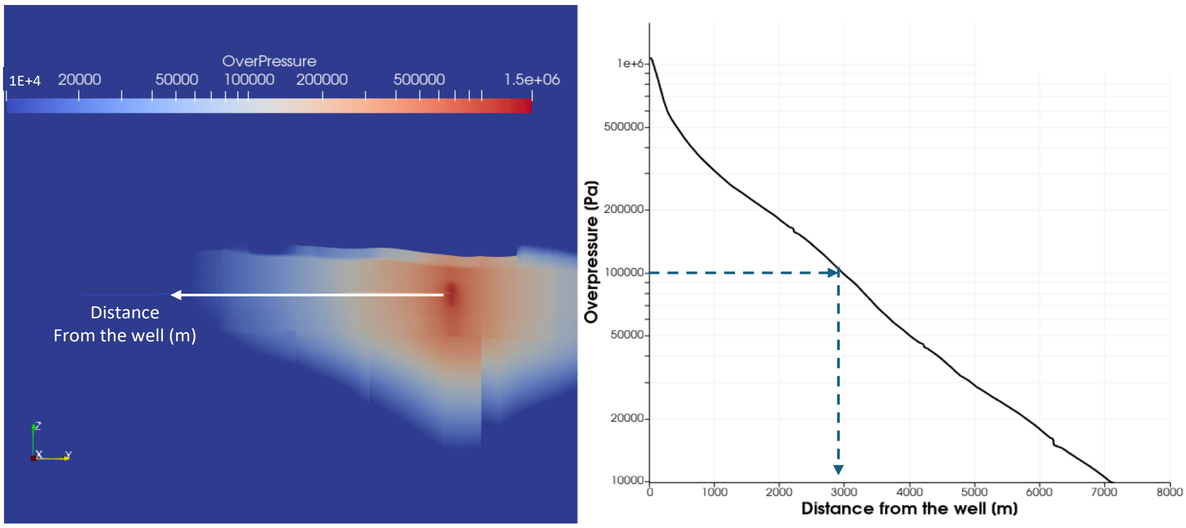

Figure 4.3 Pressure increase above the initial pressure due to CO_2 pilot injection (300 kt/y) for the base case scenario at the end of injection (4 months) (D3.3)

[2] https://www.petex.com/pe-engineering/ipm-suite/prosper/

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4.1.3 Capture at the CO_2 source

The foreseen CO_2 source does not require any capture equipment due to the Steam Methane Reforming process operated at the plant. The average composition is assumed to be 99% CO_2 and 1% H_2 as indicated in the deliverable D4.2 (Canteli *et al.,* 2024). The outlet pressure from the process is at about atmospheric pressure and the process outlet temperature is assumed to be 20°C as indicated in the deliverable D4.2.

Nevertheless, the CO_2 must be compressed and cooled at the plant gate to allow to reach the well head at the appropriate pressure and temperature conditions. The corresponding process flow diagram is shown in Figure 4.4. A four-stage compression is required to meet the expected inlet pipeline pressure which is set to meet the expected downhole conditions at the well (see section 4.1.2).

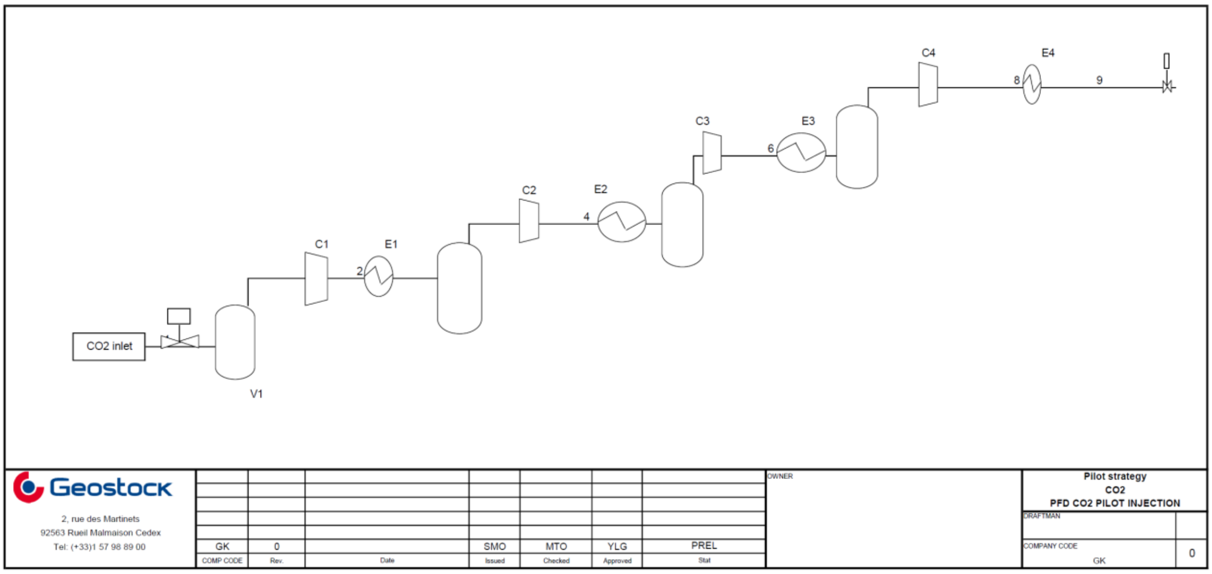

Figure 4.4 Conceptual compression process flow diagram at the plant where Ci represents the compression stage, Ei the flash stages and Vi the drums required to remove any accidental liquid drop out.

4.1.4 Transport

As indicated previously, there may exist pressure interferences between the waste-water disposal and CO_2 injection wells as they are targeting the same formation. Consequently, the down-hole injection locations for the CO_2 need to be distant by about 3 km in the worst-case scenario obtained from the deliverable D3.3 (Chassagne, 2024). Using the most favourable injection location identified in D3.3, the topography of the pipeline could be obtained which shows only a negligible change along the CO_2 pipeline: maximum variation is about 8 meters on a mostly downward trend as illustrated in Figure 4.5.

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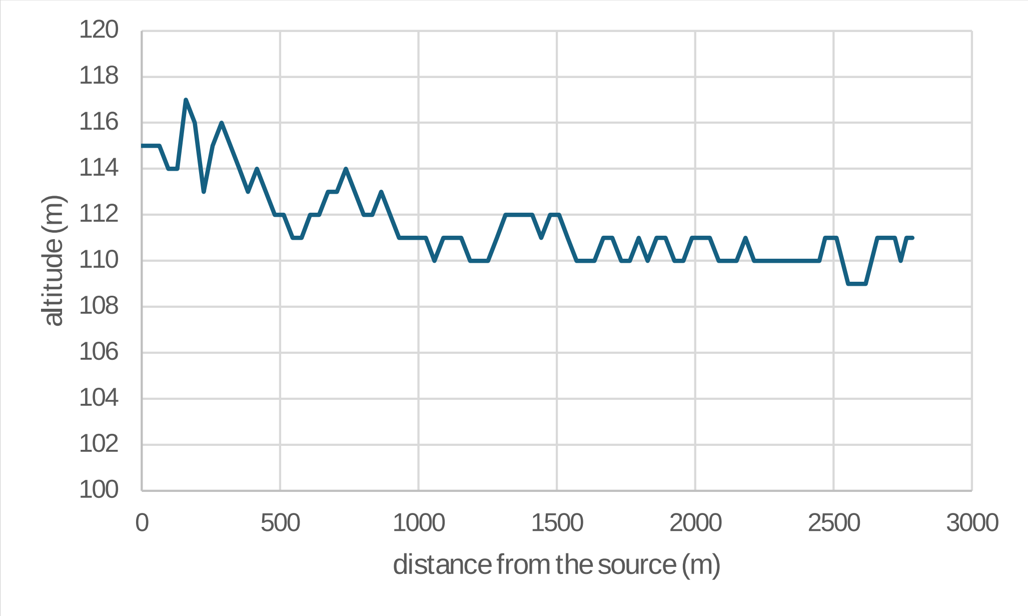

Figure 4.5 Topographic changes between the plant and well-head location of the CO_2 injection well.

4.1.5 Assumptions and Economics for the capture and transport chain for the final scenario

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.

This model requires a limited set of information to evaluate the CAPEX and OPEX of the CO_2 pipeline such as inlet temperature, pressure, pipeline characteristics (length, diameter) and assumptions for financial parameters summarized in Table 4.4.

Table 4.4 Physical assumptions for pipeline cost model for the French region from PilotStrategy deliverable D4.2

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 CAPEX for the pipeline transport chain described above is shown in

Table 4.5 as follows:

Table 4.5 Estimated CAPEX for pipeline cost model for the French region from PilotStrategy Deliverable D4.2

Pipeline	($M€_{2025}$)

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Pipeline	4.5

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 compression as illustrated in Table 4.6 and are escalated to 2025.

Table 4.6 Conditioning equipment cost for the ammonia plant for the French region from D4.2

Ammonia plant equipment cost	French case (M€$_{2025}$)
Inlet water knockout for compression	0.01
CO_2 compression	8.6

The drying equipment mentioned in the deliverable D4.2 is not required given the quality of the CO_2 at the emission plant.

The assumption for costs escalation to 2025 follow the pipeline cost models:

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

Where the parameters are summarized in Table 4.7

Table 4.7 Assumptions for subsurface plant costs for the French region from PilotStrategy deliverable D4.2

Parameter	Value	Reference
yearly escalation rate	5.12%	US Bureau of Labor Statistics[3]
€/$ exchange rate	0.9041	September 2, 2024
Average EU27 inflation rate	2.2%	European Central Bank August 2024[4]
reference year	2021	Hughes & Zoelle (2022)
project year	2025	

4.2 Lusitanian Basin (Portugal)

4.2.1 Final development selection

The case for the Lusitanian Basin CCS project, 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. This scenario considers (1) an intermittent injection

[3] https://www.officialdata.org/us/inflation/2021?amount=1
[4] https://www.ecb.europa.eu/stats/macroeconomic_and_sectoral/hicp/more/html/data.en.html

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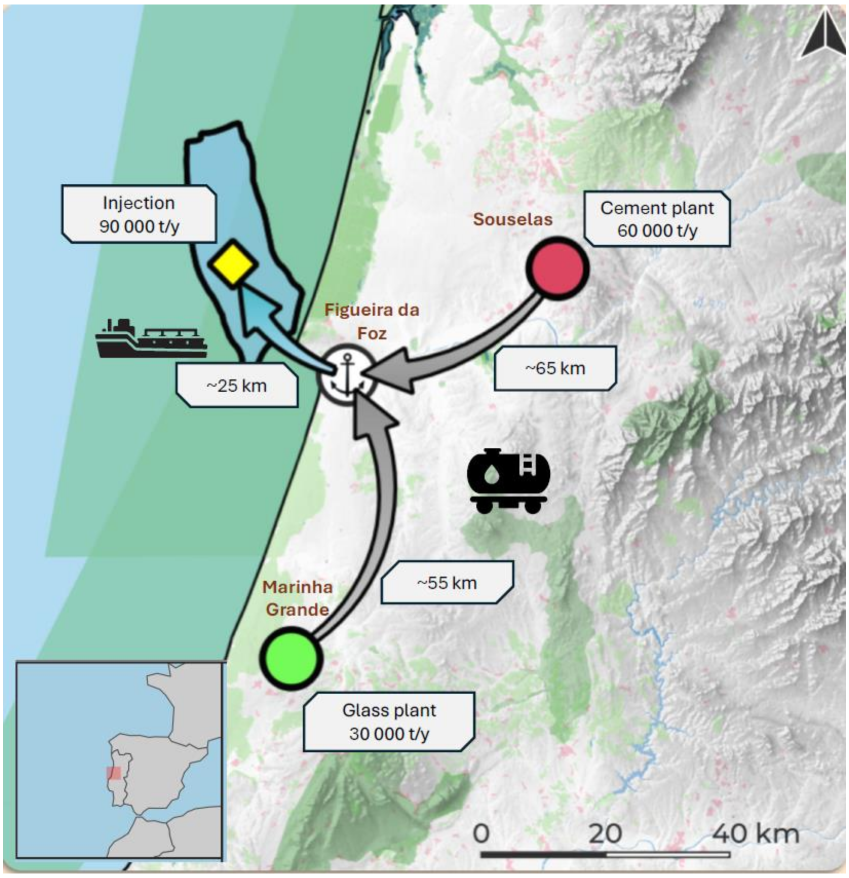
associated with train and ship transport for the pilot phase, and (2) continuous injection from the Figueira da Foz port with offshore pipeline transport (23 km) during commercial phase.

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 (**Erreur ! Source du renvoi introuvable.**). It is also considered a limited amount of 60-90 kt CO_2 per year transported by train to a hub and then, by ship, avoiding pipeline transport during pilot motivated by the subsurface uncertainties to be de-risked and the regulatory gaps still associated with this option.

Figure 4.6 Location of the main local CO_2 emitters, previously identified in StrategyCCUS (Mesquita et al., 2024)



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 CO_2 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 (Final Investment Decision) 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 4.7).

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4.2.2 Capture source

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 (Figure 4.6).

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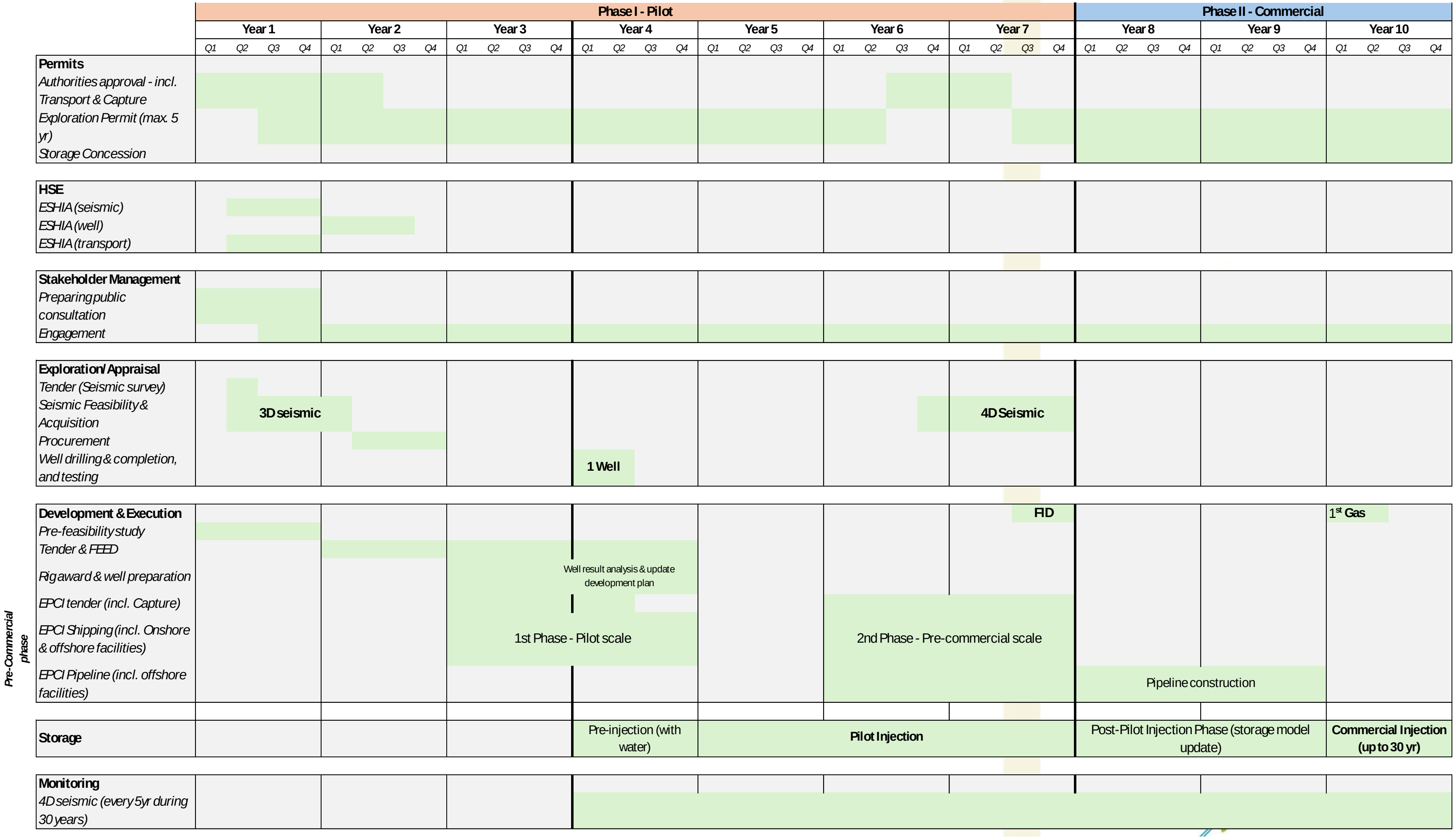

Figure 4.7: Preliminary planning of the Portuguese region

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4.2.3 Transport

The project focuses on cost-effective CO_2 transportation by utilising railway infrastructure to deliver CO_2 to Figueira da Foz (**Erreur ! Source du renvoi introuvable.**). Trains with a capacity of 4,000 tonnes each will complete round trips in 12 hours. The CO_2 will be transported in a liquified state at 6.6 bar and -50°C, necessitating a license extension after the first year due to legal limits. The system aims to align with port and offshore injection well conditions, minimising intermediate storage and reconditioning costs, thus maintaining CO_2 at its original pressure and temperature throughout the process.

To enhance operational efficiency, the transport system is meticulously aligned with the conditions required at the Figueira da Foz port and the offshore injection well. This alignment eliminates the need for intermediate storage or reconditioning at the port, thereby reducing both costs and complexity.

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

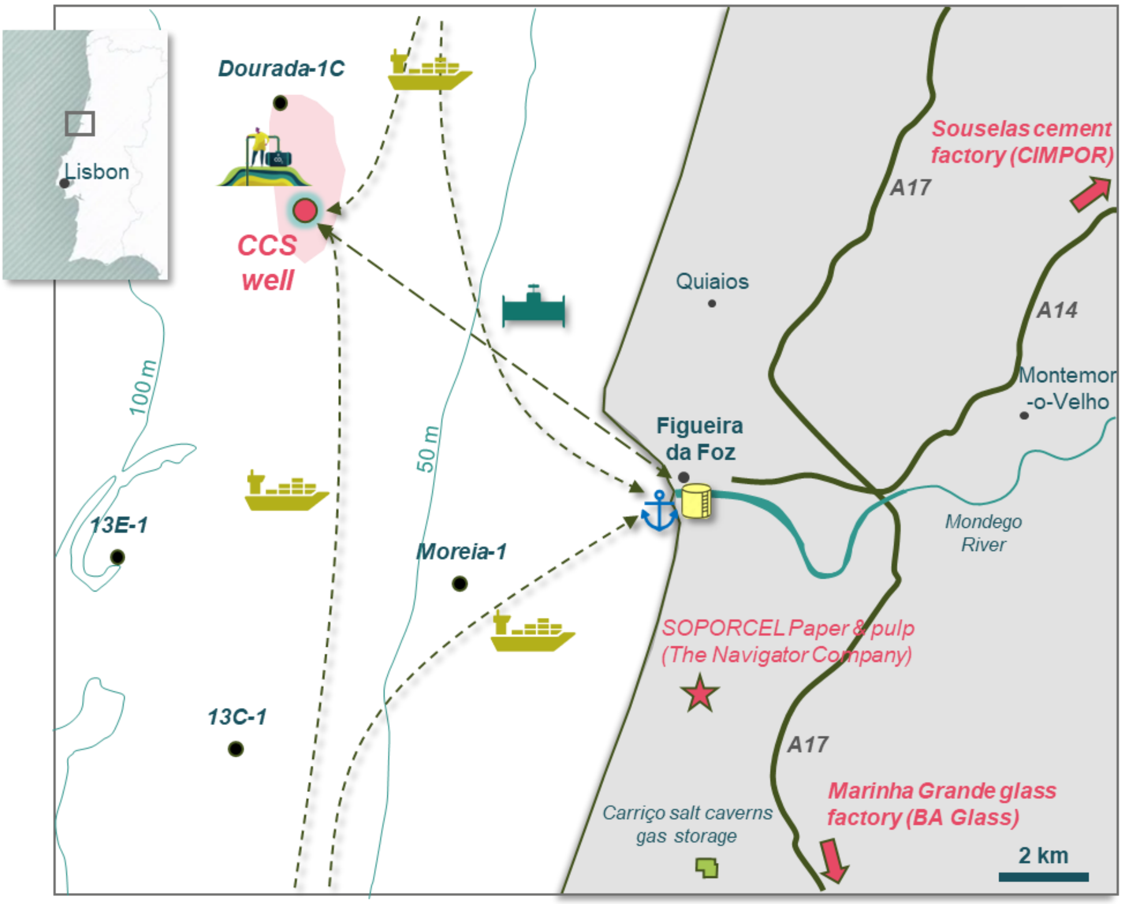

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Figure 4.6 CO_2 transportation routes from the Figueira da Foz port to the injection site.

Transporting CO_2 via pipeline (Figure 4.6) offers a technically feasible option but 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 require an 8- or 10-inch diameter. However, such a pipeline would necessitate significant investments in conditioning facilities at Figueira da Foz, even during the low-volume pilot phase, resulting in disproportionately high CAPEX for a project handling only 270 kt of CO_2.

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

4.2.4 Storage

As described in the deliverables D2.7 (Wilkinson, 2023) and D3.3 (Chassagne, 2024), the team focused on maturing Q4-TV1 prospect, at the Torres Vedras Group reservoir, composed by alternating sandstone and shale (Figure 4.7).

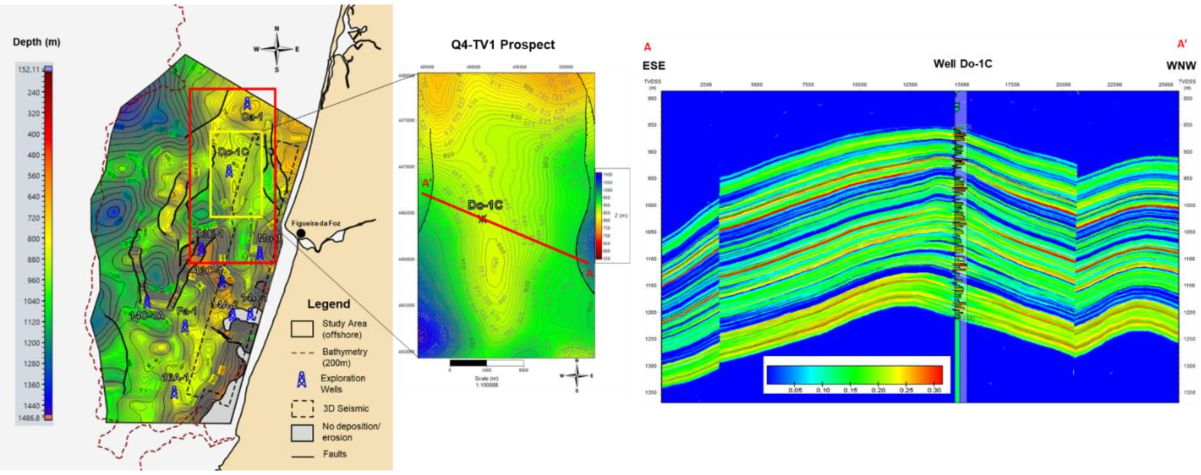

Figure 4.7 Map of the top of the Torres Vedras Group reservoir structure illustrating the outlines of the study area of the 3D static model's boundary (red rectangle) and the reservoir model boundary covering the area of the Q4-TV1 prospect (yellow rectangle). The cross-section through the Q4-TV1 prospect illustrates the reservoir effective porosity of the static model (median) and at the location of the legacy well Do-1C, and the existing faults.

The reservoir model, essential for CO_2 injection and storage optimisation, incorporates geological and petrophysical data, fault mapping, and dynamic simulation parameters. This comprehensive model enables effective simulation of CO_2 behaviour post-injection, accounting for structural features and potential migration pathways, thus addressing risks associated with CO_2 injection in the reservoir.

Optimization techniques focus on maximising CO_2 mass injection while mitigating risks, with the optimal scenarios ensuring that the CO_2 plume does not reach legacy wells or faults over a 1000-year period. The optimisation results, particularly refinement 200, demonstrated successful outcomes with approximately 16Mt of CO_2 total mass injection, providing critical insights for future CO_2 storage projects.

Sensitivity analysis identified crucial parameters impacting injection performance, guiding informed decision-making for CO_2 storage projects. Further studies are recommended to refine reservoir

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boundary conditions, obtain relative permeability curves, and perform detailed geomechanical analyses to assess fault reactivation potential, ensuring safety and efficiency in CO_2 storage implementation.

4.2.5 Well design

Results of the injection simulations described in the deliverable D3.2 (Bouquet, 2024) indicate that Bottom Hole Pressure (BHP) notably has the most significant impact on injection capacities, reflecting its pivotal role in managing subsurface pressures. Geomechanical assessments are essential for characterising the capacity of the injection site, and although the current methodology is simplistic, further detailed modelling is planned to address the maximum permissible pressure buildup.

Perforation depth and thickness are critical as they relate to the transmissivity of the reservoir, indirectly influencing the pressure behaviour around the injection well. These factors are controllable within the well design process, which aims to position the screened sections of the well within the most permeable and advantageous layers.

Furthermore, anisotropy in permeability and its influence on pressure propagation significantly affects the injection rate. This sensitivity underscores the importance of conducting an appraisal well and hydraulic testing to better understand and manage these parameters.

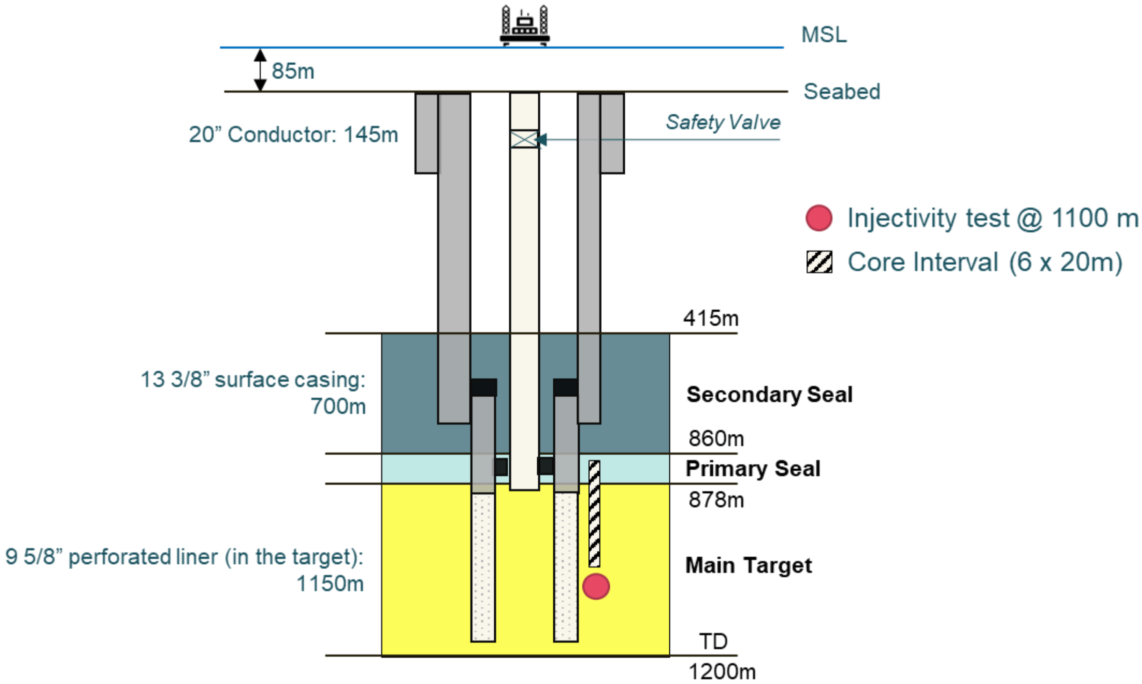

Figure 4.8 Preliminary well design, to be updated and detailed with the results of the dynamic simulations and fate of CO_2 plume in the long-term, to be conducted in WP3.

Future work must focus on refining the static and dynamic simulation models to construct a well design that optimally balances these factors (preliminary design was initially made before the injection simulations, in Figure 4.10). Obtaining more detailed relative permeability curves, performing comprehensive geomechanical analyses, and refining the reservoir boundary conditions are crucial steps in this process. These efforts will ensure the safety, efficiency, and success of CO_2 storage implementation.

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4.2.6 MMV

The MMV plan is still in development due to ongoing risk analysis at the time of this report. For scenarios in this area, the MMV plan will follow recommended procedures for similar projects. In the Lusitanian basin, several legacy wells, including the Dourada-1 well within the P50 prospect outline, play a role in current dynamic simulations to ensure the CO_2 plume does not reach the well long-term. Dourada-1, plugged and abandoned in the 70s, is not considered for monitoring. Although drilling new observation wells could be beneficial, their high cost is a major drawback, prompting consideration of offshore alternatives for effective site monitoring.

During the pilot phase, 4D seismic will be crucial for tracking the CO_2 plume's subsurface movement. Additionally, along-well monitoring stations and seabed monitoring (e.g., piston cores, ROV inspection) will likely be part of the MMV plan. Observation wells may be considered in later stages for enhanced reservoir understanding, despite their cost. For commercial development, baseline monitoring with long-term 4D seismic acquisition will be essential, tracking plume evolution from pre-injection through to post-operation. Preferred offshore baseline monitoring includes along-well CO_2 sensors, seabed monitoring, and regular 3D seismic acquisition to track plume dispersion over time, adhering to regulatory standards.

Due to uncertainties in reservoir performance and seal integrity, MMV strategies to accelerate pilot development will emphasize along-well monitoring. Recent advances in well-based monitoring focus on petrophysical measurements, core plugs, and permanently deployed sensors for repeated geophysical surveys, capturing temporal subsurface changes. Understanding coupled subsurface processes—hydrological, mechanical, and geochemical—is vital to ensure the long-term containment of stored CO_2 throughout the project's lifecycle.

4.2.7 Injection strategy

The results from the iterative optimisation process (D3.2, Bouquet, S. 2024) revealed that the optimal well location, defined by refinement 491, offers a high CO_2 storage capacity, with the capability to inject approximately 32,910,700 tons of CO_2 over a 30-year period. This location was chosen based on several criteria:

1. Maximising Storage Capacity: Refinement 491 achieved the highest well mass gas injection total, meeting the target of 50 million tons of CO_2.
2. Risk Mitigation: The chosen well location ensures that the CO_2 plume does not reach the abandoned legacy well or intersect with the existing faults (F2 and F5), maintaining the integrity and safety of the storage site.
3. Geological Suitability: The location aligns well with the geological features and variations considered, ensuring optimal interaction with the reservoir characteristics.

This approach ensures that the selected well location (Figure 4.11) not only maximises CO_2 storage capacity but also addresses potential risks associated with CO_2 injection. The iterative process of 948 iterations (including both scoping and refinements) allowed for comprehensive exploration and fine-tuning of parameters, leading to a robust and reliable optimisation outcome.

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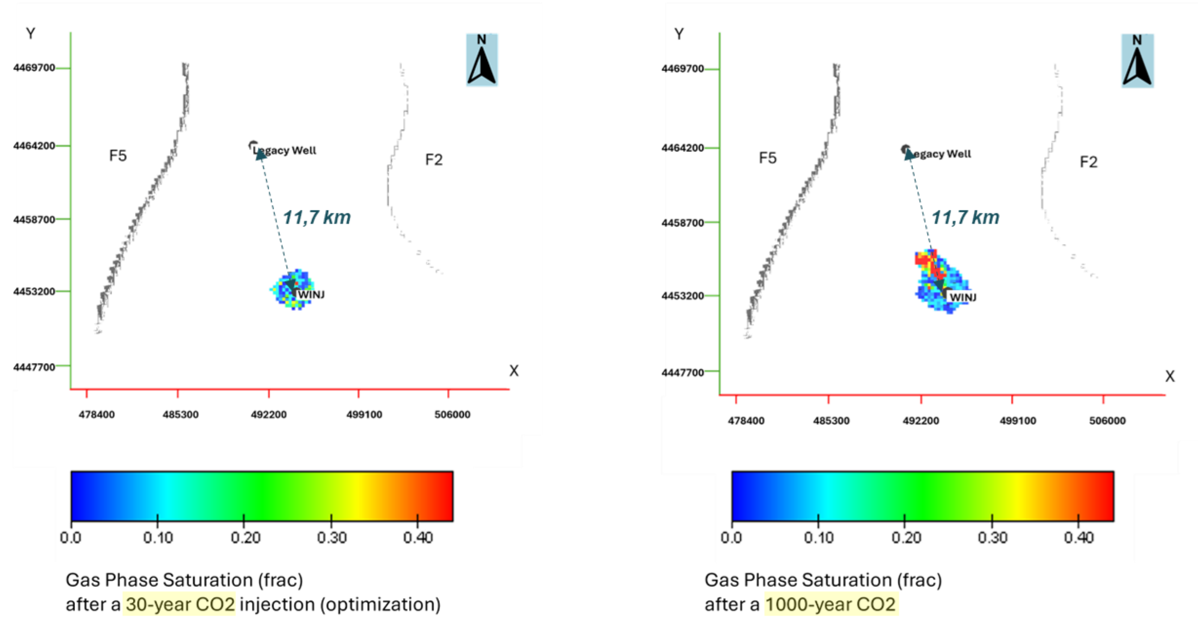

Figure 4.9 Simulations over short (30 years) and long (1,000-year post-injection) periods of time suggest CO_2 plume does not extend to the Dourada-1C legacy well

The selected well location ensures that the CO_2 plume remains within the prospect-area of interest, avoiding the abandoned legacy well and existing faults. The focus on optimising well location in 3D space, with particular attention to the Z-direction (perforation depth), proved crucial in achieving these outcomes.

4.3 Ebro Basin (Spain)

4.3.1 Final development selection and description

Ebro basin selected scenario is based on a pre-commercial phase (pilot scale) and commercial phase with full life cycle. There is not selected emitter although few potential ones are identified in the proximity (<60km). It is assumed CO_2 stream impurities compatible with Lopín storage site and no limitations due to CO_2 quality.

The selected development is a flexible one based on the current uncertainty of the potential storage volume, in a range between 2 Mt and 26 Mt. It is proposed an initial phase of 1 year (pilot phase) with a well, injecting 0.03 Mt/year, and a commercial phase with 0.5 Mt/year thereafter until reach maximum estimated capacity.

The exploration phase includes (Figure 4.10):

- 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 23 Mt-case (and 0.07 in others)
- Injection facilities design and building.

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

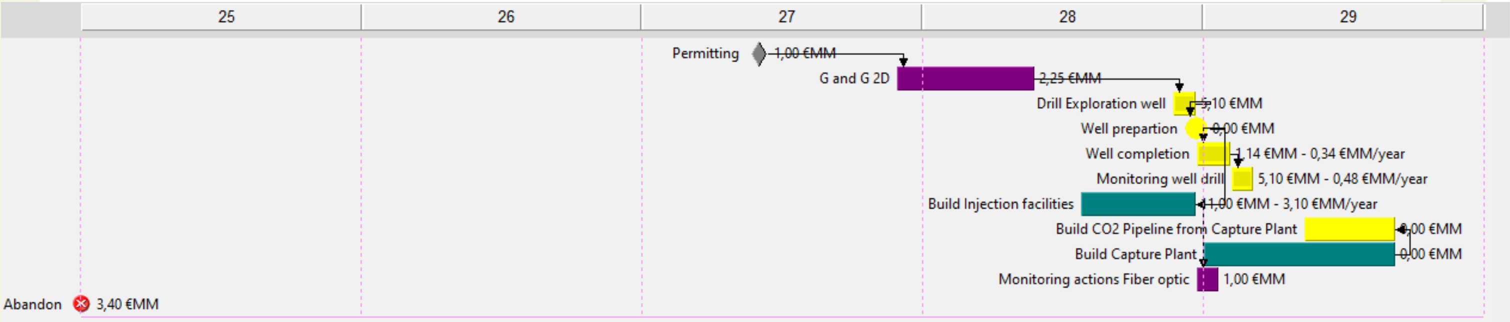
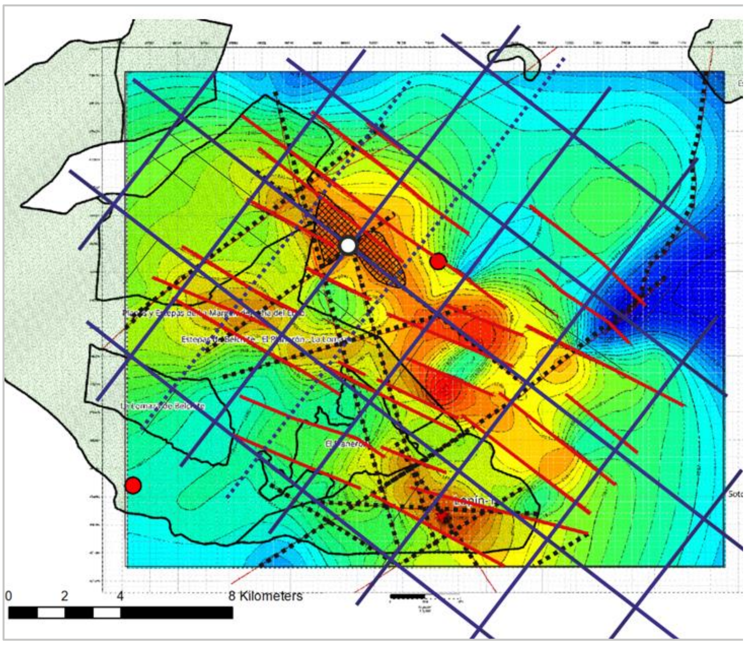


Figure 4.10 Minimum costs scenario activities schedule starting in 2025 works for permitting

The planned seismic acquisition involves a 2D survey aimed at better delineating the structure and complementing the pre-existing 2D data. New 2D lines will be added to the existing ones. The lines to be acquired will be designed with a spacing of 2-4 km (dip) and 4 km (strike). A total of 143 km dip and 107 km strike are planned for acquisition (Figure 4.11).



- 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

REPSOL

Figure 4.11 2D acquisition design and costs estimation for minimum costs scenario

4.3.2 Capture source

The closer emitters are listed in the table (Table 4.8,

Table 4.9 and Figure 4.12Figure 4.12: close-by emitters, last reported CO_2 emissions with numbers in red (CO_2t, year 2022). Greenish polygons are the Natura 2000 protected zones.) [5]

[5] https://prtr-es.es/Informes/InventarioInstalacionesIPPC.aspx

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Table 4.8: list of closer emitters to the planned injection site.

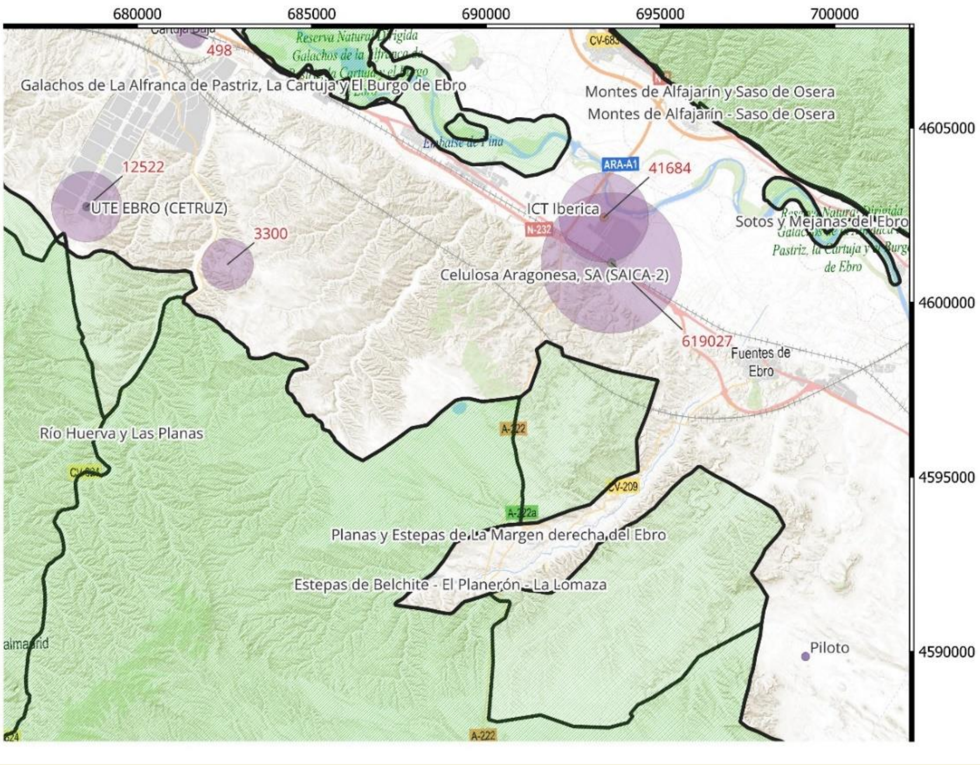
Approx. distance. (Km)	Code PRTR	Industrial Complex name
35	1016	VERALLIA - ZGZ (ANTERIOR S.GOBAIN VICASA)
35	2761	SAICA 1
14	2762	**SAICA PAPER EL BURGO DE EBRO**
28	2768	INDUSTRIAS QUIMICAS DEL EBRO, S.A.
25	4095	COMERCIAL INDUSTRIAL ARIES, S.A.
25	173	EVONIK LA ZAIDA
36	2787	TEREOS STARCH & SWEETENERS IBERIA, S.A.U.
26	7849	**UTE EBRO (CETRUZ)**

Table 4.9: GHG emissions reported to the Spanish ministry from 2015 to 2022.

	CO_2 (t/year)			CH_4 (t/year)			NOx /NO_2 (t/year)		
	Max	**Min**	**Avg**	**Max**	**Min**	**Avg**	**Max**	**Min**	**Avg**
Verallia	65,622	53,962	60,044				526	183	270
SAICA 1	257,860	219,204	247,899				737	78	265
SAICA PAPER	778,359	177,149	327,632				548	103	181
QUIMICAS DEL EBRO	73,821	62,799	66,408				142	47	81
ARIES	104,902	83	66,420				152	34	61
EVONIK	67,723	35	35,443				25	10	15
CETRUZ	15,064	4850	10,198	968	173	610	21	8	13

The emitters highlighted in yellow are the ones initially contemplated in this project. Nevertheless, other emitters can be considered in future appraisals.

Figure 4.12: close-by emitters, last reported CO_2 emissions with numbers in red (CO_2t, year 2022). Greenish polygons are the Natura 2000 protected zones.



4.3.3 CO_2 specifications and facilities design

CO_2 quality is based on ISO-27913 “Carbon Dioxide capture, transportation and geological storage - Pipeline transportation systems”[6]. This international standard establishes the maximum impurities content ranges that must not be exceeded to ensure "Flow assurance" including the integrity of pipelines and equipment working with CO_2 streams (Figure 4.13).

Table A.1 — Indicative levels of main CO_2 impurities and factors driving these levels

Species	Indicative levels (volumetric composition in ppmv, unless stated as mol%)		
CO_2	>95 mol%[a]		
H_2O	Corrosion, 20 to 630[b], Hydrate, <200[c,d]		Avoiding the formation of corrosive phases and solids in the pipeline is essential for safe operation of the CO_2 pipeline system. There are a number of possible cross-chemical reactions that have the potential to form sulfuric/sulfurous acid, nitric acid and elemental sulfur when water and SO_2, NO, NO_2, O_2 and H_2S are present[33], also N_2O, N_2O_4[40]. Presently, there is no publically available model that can predict which of the reactions are thermodynamically and kinetically possible and favourable when the impurities are mixed. Since the maximum concentration of a single impurity will depend on the concentration of the other impurities, it is not possible due to lack of data and current understanding to state a fixed maximum concentration of a single impurity when other impurities are, or may be, present.
H_2	<0,75 mol%[e,f]	<4 % total for all non-condensable gasses, but individual contributions may also be significant	
N_2	<2 mol%[f,g]		
Ar	[f]		
CH_4	[f,g]		
CO	<0,2 mol%[j,k]		
O_2	[f,h]NB. Downstream limitations		
H_2S	<200[g,i,k]	Individual values, each below STEL,[m] but see Footnote n.	
SO_2	Health and Safety < 100[k,l]		
NO_2	Corrosion < 50[n]		
Amine		The presence of amines, MeOH, EtOH, glycols and other water soluble components (e.g. HCl, NaOH, other salts) will facilitate the formation of an aqueous phase (free water) and reduce the concentration of water in the CO_2 at which a separate aqueous phase is formed. The maximum concentrations that are acceptable will depend on the concentration of the other impurities (see above note).	
Methanol			
Ethanol			
Glycol			
C_2+	<2,5 mol%[o]		

Figure 4.13: CO_2 composition based on ISO-27913

A composition of CO_2 was selected including a certain content of typical impurities but complying with the ranges indicated in the standard above.

Based in proposed well’s location a location for the main injection plant was designated near the expected captured CO_2 incoming route. Then a route for the CO_2 injection pipelines to each well was assigned avoiding terrain obstacles. A source from electric power supply network was also identified. Distances for pipelines and electric line supply was obtained from satellite maps available connecting the injection plant site with the wells and power supply.

With the distances and locations defined, plus the composition, borehole pressure and temperature conditions of each well and a mass flow per case, a model in Aspen HYSYS V12.1 was created to size the pipelines and equipment power required to inject the CO_2 stream into the reservoir.

Aspen HYSYS v12.1 is a powerful process simulation software widely used in the energy industry for optimising upstream, midstream, refining, and crude oil-to-chemicals processes. It is trusted for its comprehensive capabilities, making it the industry's preferred process simulator for over 40 years.

Some of the impurities listed in the composition of CO_2 were not included (set to 0%) since the most common Equation of State used for hydraulics calculations (Peng & Robinson, 1976) was not able to run with them included. All those that allow running the simulation in a steady state and obtaining results for sizing the equipment and pipelines have been included. Final CO_2 composition used for HYSYS modelling is listed in the following table (Table 4.10).

[6] https://www.iso.org/standard/84840.html

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Once pipelines and equipment were dimensioned with HYSYS, a model of each case was created in QUE$TOR 2023 to obtain a Class 5 cost estimate for CAPEX, OPEX and ABEX.

Regarding the design of the pipelines, the ISO-13623 standard "Petroleum and natural gas industries - Pipelines transportation systems"[7] has been used to determine the material and wall thickness of the pipeline once the diameter has been determined according to the erosional velocity and the permissible pressure drop according to the simulations run in HYSYS. The selected material was grade X52 carbon steel according to the API 5L "Specification for line pipe"[8] equivalent to ISO 3183[9].

Table 4.10: Final CO_2 composition used for HYSYS modelling

Element	Mole Fraction
CO2	0.9617830772
H2O	0.0000000000
Oxigen	0.0000400417
Nitrogen	0.0200208621
Methane	0.0100104311
Hydrogen	0.0050052155
Argon	0.0010010431
CO	0.0005005216
H2S	0.0000050052
NO2	0.0000050052
NO2	0.0000050052
SO2	0.0000050052
SO3	0.0000050052
Ethane	0.0001001043
Propane	0.0001001043
i-Butane	0.0001001043
n-Butane	0.0001001043
i-Pentane	0.0001001043
n-Pentane	0.0001001043
n-Hexane	0.0001001043
n-Heptane	0.0001001043
n-Octane	0.0001001043
n-Nonane	0.0001001043
n-Decane	0.0001001043
Benzene	0.0000000200
Toluene	0.0000000200
E-Benzene	0.0000000200
o-Xilene	0.0000000200
m-Xilene	0.0000000200
TEGlycol	0.0000000000
Methanol	0.0005005216
Ethanol	0.0000000000
Formaldehyde	0.0000000000
FormicAcid	0.0000000000
AceticAcid	0.0000000000
Ammonia	0.0000100104
HCN	0.0000020021
MDEAmine	0.0000000000

[7] https://www.iso.org/standard/61251.html
[8] https://www.apiwebstore.org/standards/5L
[9] https://www.iso.org/standard/76676.html

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For all the cases evaluated, the CO_2 is delivered in dense phase (Liquid phase) to the Injection (pumping) plant. This pipeline and the CO_2 capture are not in scope as will be part of emitter work scope. Maximum probable temperature for CO_2 delivered to the plant is 30ºC and to be in dense phase the pressure is set at 85 barg.

4.3.4 Transport & storage

Based on the pre-selected cases (Table 5.9, D4.9, [Canteli *et al.* 2025]) for delineating the transport options and surface facilities, two extreme scenarios have been considered: 2 Mt with 1 well and 26 Mt with 2 wells.

Table 4.11 Pre-selected scenarios (Deliverable 4.9)

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

Two extreme scenarios have been modelled, first one for 1 well, 2.1 Mt during 30 years, and second one for 2 wells, 27 Mt during 30 years.

4.3.4.1 1 well. 2 Mt total injected mass

For this case, it is considered that the CO_2 arrives at the pumping station at a temperature of 30ºC (worst case scenario) and a pressure of 85 barg (dense phase). Subsequently, it is driven by a pump that requires 81 hp to rise the head of CO_2 stream to 192 barg @62ºC to reach the wellhead through a pipeline of nominal diameter of 2 inches and standard schedule (3.91 mm wall thickness). Considering pressure losses and hydrostatic pressure, final conditions at reservoir level are 305.8 bar and 69 ºC (Figure 4.14)

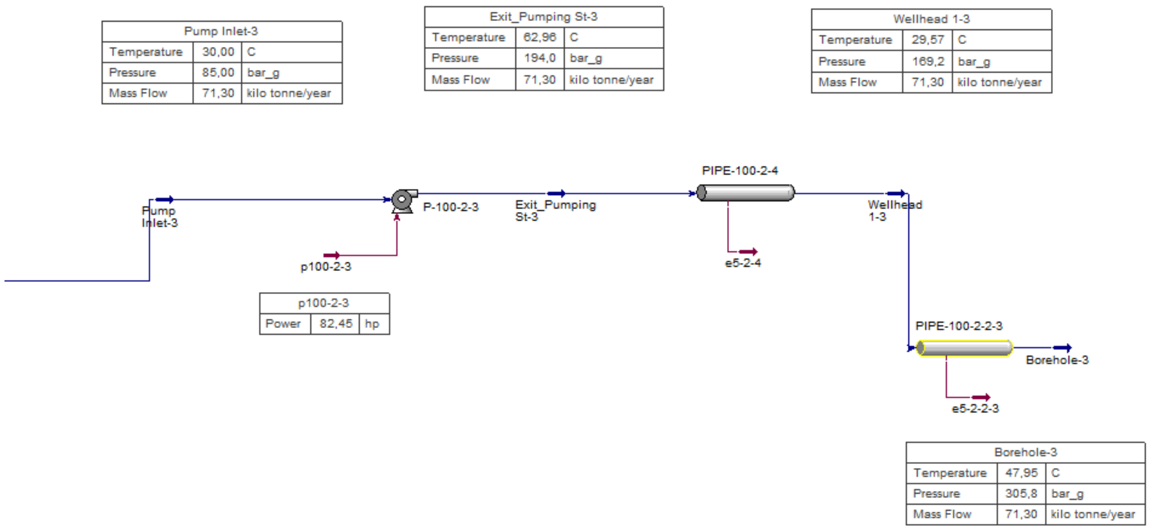

Figure 4.14: Scheme for 1 well case (2.1 Mt).

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Then the Que$tor model is built to obtain the cost estimate:

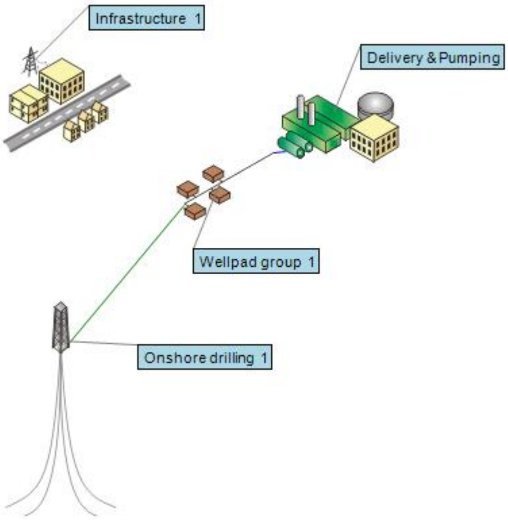

Figure 4.15: QUE$TOR model for 1 well case (2.1 Mt).

For developing this case, this is the equipment that is required (Table 4.12, Figure 4.16) in the injection site.

Figure 4.16: Equipment needed for 1 well case (2.1 Mt).

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Table 4.12: Parameters for 1 well case (2.1 Mt).

Electric Line	2,070	m
Pipeline 2	5,350	m
Injectors	1	Unit
Mass to inject	2,140,000	tonnes
Duration	360	months
Flow Rate	71.333	ton/year
BHP	305	Barg

Table 4.13 shows estimated costs, which are composed by Operating Cost (OPEX), Capital Expenditures (CAPEX) and Abandonment Cost at the end of the project (ABEX).

Table 4.13: Estimated Cost for 1 well case (2.1 Mt).

CAPEX (MEUR)	Max Well 1
G&A (PMT)	0.45
Pre-sanction cost (FEED,…)	0.72
Post-sanction cost	0.43
G&A Total	1603.87
Delivery & Pumping Plant	6580.04
Infrastructure (power line, office,…)	0.
Wellpad & pipeline	1810.91
Facilities Total	8980.43
Drilling CO_2 Injector Well 1	5452.63
Drilling Total	5452.63
Total CAPEX	16036.93
OPEX (MEUR)	
Operating Personal	27665.46
Inspection & Maintenance	1329.03
Logistics & Consumable	30215.02
Insurance	2142.72
Field Project Cost	11581.52
Total OPEX (M$)	72933.75
Operation (years)	27.12
OPEX avg.M$/year	2431.12
ABEX (MEUR)	
Abandonment Wells	0.35
Decommissioning Facilities	2785.53
Total ABEX	3131.80
Total	**92102.48**

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4.3.4.2 2 wells. 27 Mt total injected mass

For this case, the CO_2 arrives at the pumping station at the same conditions as previous case (30ºC and 85 barg, dense phase). Subsequently, it is driven by a pump that requires 1515 hp to rise the head of CO_2 stream to 240 barg @74ºC to reach the two (2) wellheads through independent pipelines, one of 812 m length and a nominal diameter of 3 inches and schedule standard (5.49 mm wall thickness), and the other of 8.72 km length and nominal diameter of 4 inches and schedule standard (6.02 mm wall thickness). Considering pressure losses and hydrostatic pressure, final conditions at reservoir level are around 302 and 309 barg (Figure 4.17).

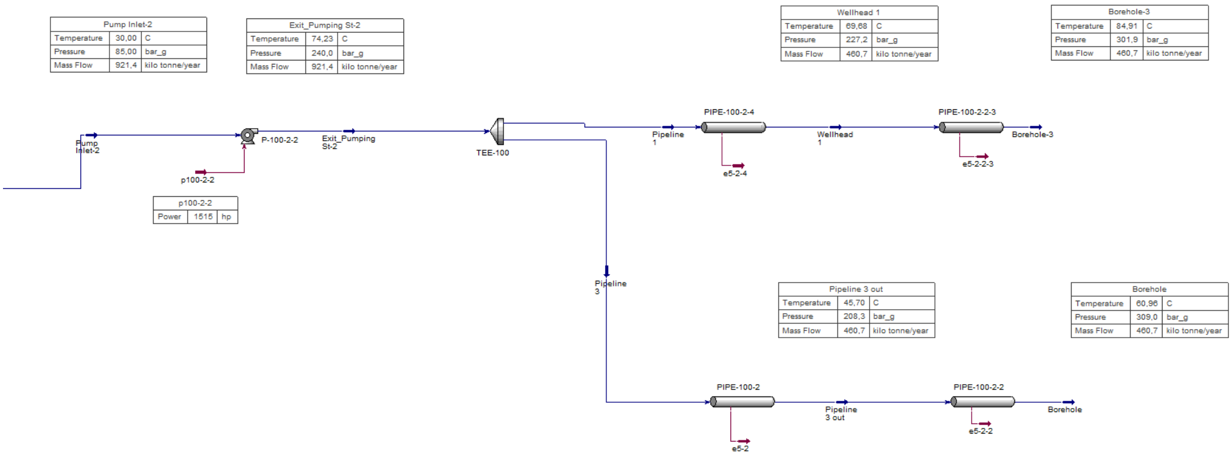

Figure 4.17: Scheme for 2 well case (27.6 Mt).

Then the Que$tor model is built to obtain the cost estimate:

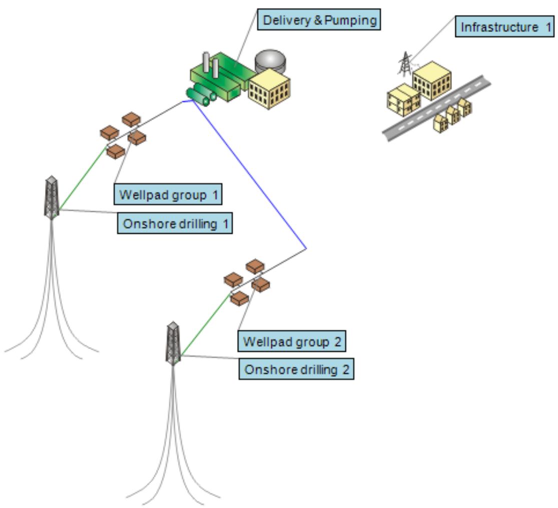

Figure 4.18: QUE$TOR model for 2 wells case (27.6 Mt).

For developing this case, this is the equipment that is required (Table 4.14, Figure 4.19)

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Figure 4.19: Equipment needed for 2 wells case (27.6 Mt).

Table 4.14: Parameters for 2 wells case (27.6 Mt).

Electric Line	2,070	m
Pipeline 1'	812	m
Pipeline 3	8,715	m
Injectors	2	units
Mass to inject	13,820,000	tonnes per well
Duration	360	months
	30	years
Well1	460,666	ton/year
Well3	460,667	ton/year
Flow Rate	921,333.3	ton/year
BHP	305	Barg
Depth	1.750	m

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Table 4.15 shows estimated costs, which are composed by Operating Cost (OPEX), Capital Expenditures (CAPEX) and Abandonment Cost at the end of the project (ABEX).

Table 4.15: Estimated Cost for 2 wells case (27.6 Mt).

CAPEX (MEUR)	2 Wells Case
G&A (PMT)	1082.21
Pre-sanction cost (FEED,…)	1704.23
Post-sanction cost	1022.54
G&A Total	3808.97
Delivery & Pumping Plant	15520.68
Infrastructure (power line, office,…)	1457.41
Wellpad & pipeline	4664.25
Facilities Total	21642.35
Drilling CO2 Injector Well 1	6222.02
Drilling CO2 Injector Well 3	6222.02
Drilling Total	12444.03
Total CAPEX	37895.35
OPEX (MEUR)	
Operating Personal	30920.22
Inspection & Maintenance	3227.64
Logistics & Consumable	131926.27
Insurance	5126.25
Field Project Cost	26797.52
Total OPEX (M$)	197997.90
Operation (years)	27.12
OPEX avg.M$/year	6599.93
ABEX (MEUR)	
Abandonment Wells	0.69
Decommissioning Facilities	6180.43
Total ABEX	6872.97
Total	**242766.22**

4.3.5 Well design

All wells considered are vertical, which will drill into the reservoir in 8.5” standard diameter which would facilitate the use of wireline tools and standard completions. The Figure 4.22 shows a first draft of this well design. As stated in the D4.9 (Canteli *et al.* 2025) this well could cost about 5.2 MEUR.

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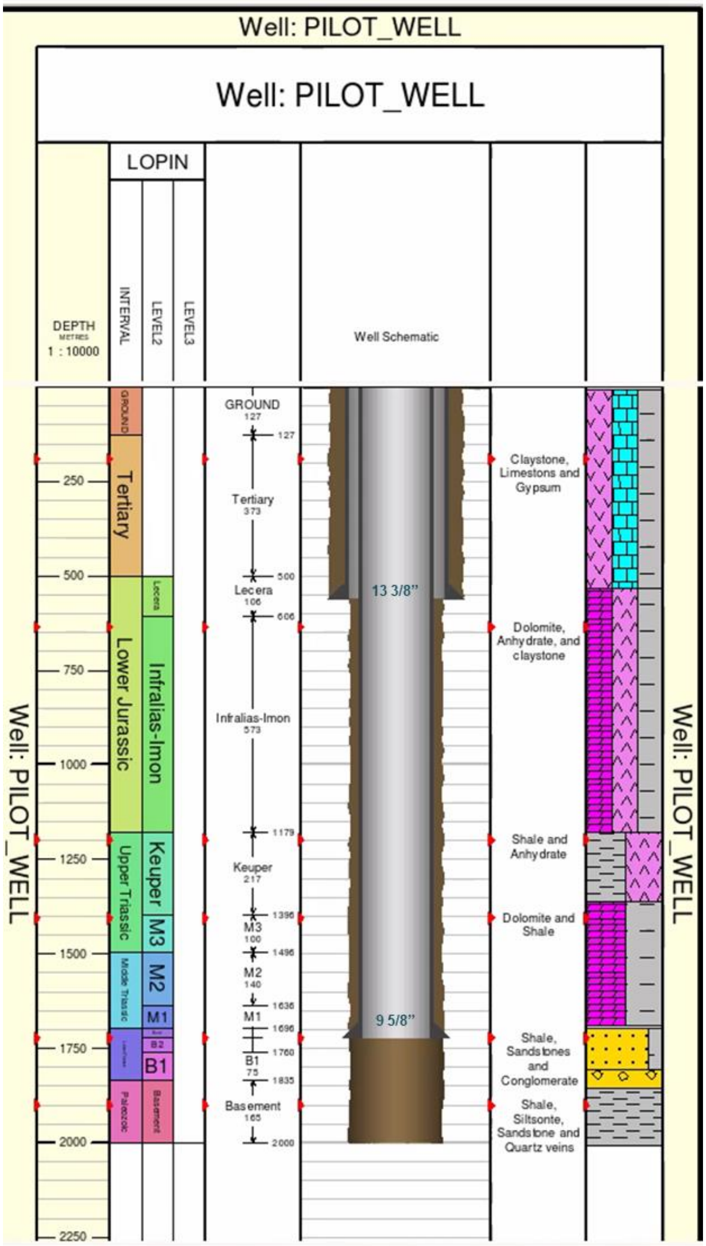

Figure 4.20: Lopin area vertical well first draft.

4.3.6 MMV

The MMV plan should be site-specific and adaptive. At this stage of the project, this plan is still being designed and it will be fed by other work packages results (*i.e.,* WP 2, 3, 5, 4 and 6).

Following Quest CCS project (Bourne *et al.* 2014) a MMV project could have these different proposes:

- **Ensure conformance** to indicate the long-term security of CO_2 storage. This implies that CO_2 plume development inside the reservoir is consistent with the models, updating these models if needed. It will also provide the monitoring data necessary for CO_2 inventory reporting.
- **Ensure containment**. Verifying containment and the absence of any undesired environmental effects. Establish an early warning system for any unexpected loss of containment.

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- **Comply with the local regulation**.

In EPA's [10] web are summarised some of the methods and objectives of a MMV plan in a graphic way. So far, the scenario includes a monitoring well outside the planned plume expansion for the reservoir observation.

4.3.7 Injection strategy

Initial injection test of 0.03 Mt/yr for 3 years; 0.5 Mt/yr thereafter if 27Mt-case (and 0.07 Mt/yr in others) (D4.9, Canteli *et al.,* 2025).

4.4 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.

4.4.1 Final development selection

The final phase of developing the CO_2 Capture, Utilization, and Storage (CCUS) project in Upper Silesia needs a change in national regulation - the current provision in the annex to the Polish geological and mining law (Journal of Laws 2024.1290, consolidated text) allows the offshore storage of carbon dioxide. Ensuring participation of industry representatives and providing funding for CCUS depends on the stability of legal regulations and minimisation of physical, social and financial risks. The selection of the final development plan should include environmental aspects, as well as risk assessment, reliable characterisation of storage site, monitoring plan, involvement of local society and local authorities. Regarding transport, during pilot phase construction of pipeline wouldn't be reasonable, road transport is expected and sufficient. However, implementation of CCUS technology in larger scale requires construction of the pipeline.

Three perspectives were considered during planning of a CCS installation in Upper Silesia:

i. Within 5 years – CCS pilot on a scale 100,000 tons of CO_2/3 years (limited due to current legislation), i.e. approx. 100 tons per day:

- Geological modelling - completion of research; 3D seismic research; modelling – narrowing the area, assessment of safety.
- Effective cooperation with local politicians, involvement of the local community (representatives of offices, residents).
- A social campaign combined with repeated surveys of the population from storage sites (conducting a social information campaign, necessarily in Polish, which guarantees greater accessibility for residents of small communes and local government employees; involvement of staff from the departments of mining, geology, environmental protection, and environmental management).
- Identification of the socio-economic benefits of CCS for the local municipality (based on mining experiences; fee share, ETS savings vs. tax losses).

[10] https://www.gwpc.org/wp-content/uploads/2023/12/3014-EPA-UIC-Class-VI-Risk-Mitigation-small-graphic.pdf

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- Risk identification (mining exploitation in the Upper Silesia region - felt rock bursts, visible mining damage and destruction of buildings caused by current and completed coal mining - significant impact on public fears regarding storing CO_2 underground; necessary microseismic monitoring during and after CO_2 injection).
- Identification of potential losses (impact on local property prices).
- Selection of a CO_2 emission source aimed at maintaining industry in Upper Silesia (steelworks, waste incineration plants) and contributing to increasing social acceptance of the investment.
- Pilot installation implementation: preparation of technical documentation and obtaining the necessary administrative decisions; preparation of initial infrastructure (road construction) necessary to transport heavy equipment (drilling rigs, then CO_2 tanks).
- Construction of a pilot installation.

ii. Within 10 years

- Proving the feasibility of the pilot and investors attraction
- Transport modelling; pipelines – social acceptance of the pipeline route (underground); pipeline monitoring.
- scaling up injection in the same deposit (industrial installation) and the monitoring activity

iii. Within 50 years – monitoring after closure of a CCS landfill

Finally, the preliminary schedule includes the pilot phase as well as the commercial phase:

- modelling and characterisation 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

4.5 Macedonia Basin (Greece) conceptual scenarios

4.5.1 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 maximising opportunities for CO_2 utilization within local industries.

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4.5.1.1 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 optimising 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.

4.5.1.2 Utilisation and Market Development

To increase the project's financial feasibility, CO_2 utilisation opportunities should be prioritised. 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 minimising the total volume transferred to storage.

Formalising 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.

4.5.1.3 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.

5. Conclusions

This deliverable describes mainly from a technical point of view the selected scenario for optimum development for each region as a starting point for its maturation to be presented in the final pre-investment proposal. Only a broad overview can be given at this point due to the degree of uncertainty. Next phases of the study will provide an increased level of detail, enabling the economic evaluation of the pilots.

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