WP4 -Deliverable 4.5

From capture to the injection facilities definition: capture, transport and CO_2 stream quality

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2. Executive summary

Deliverable D4.5 is part of Work Package 4 (WP4) of the European PilotSTRATEGY project, funded by the Horizon 2020 program. Its purpose is to define the key technical elements for the development of pilot projects for CO_2 capture, transport, and injection, for the development concept selected -pilot or commercial scale-up. Five European regions are studied – only French, Portuguese and Spanish regions in detail- and this summary focuses on the cross-cutting and methodological aspects of the document.

The document integrates:

- CO_2 source characterization: identification of relevant industrial emitters in the regions.
- Capture technologies: selection of viable technologies based on industry type and gas composition.
- CO_2 stream specifications: definition of acceptable purity, pressure, temperature, and composition.
- Transport options: technical and economic feasibility of road, rail, ship, and pipeline transport.
- Reception and injection facility design: from wells to compression and monitoring systems.
- Cost estimates: CAPEX and OPEX for both pilot and commercial phases.

Paris Basin (France):

Paris basin selected scenario is only considering a pilot scale development but using commercial rate i.e. about 300 kt/year and limited to a total of 100 kt. Considering the maximum injection pressure at reservoir conditions as defined in WP3, two scenarios are considered in the design to reach the target:

- Main scenario: off-site injection with a 3-km pipeline between the CO_2 source and the wellhead and a slightly deviated well
- Alternate scenario: on-site injection with a long and strongly deviated well

The wellhead conditions are computed based upon the two designs to estimate the required compression at the CO_2 source. The CO_2 source is an ammonia plant with a pure CO_2 outlet stream considered which consequently does not require capture and conditioning equipment. The compression requires a 5-stage compressor with interstage coolers with different outlet conditions in the two scenarios: higher pressure and temperature for the alternate scenario due to the well length and deviation.

The 40-meter perforated interval in the target formation, Oolithe Blanche (Bathonian), is defined as recommended in the dynamic simulations performed in WP3 for both scenarios using a in a 4 ½" tubing in a 7'' production casing. The well sections are defined to protect sensitive Albo-Aptian aquifer covered by 2 casings, cemented up to surface. The well architecture requires 4 or 5 casing stages for the main and alternate scenario respectively. For the main scenario the well deviation is about 26° while for the alternate scenario the deviation is about 65°. Therefore, the data acquisition shall be limited in the alternate scenarios due to the well deviation.

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Lusitanian Basin (Portugal):

The main goal for this deliverable is to define and design the facility outlook and transportation for each project phase (pilot and commercial), including the cost estimation. We considered the CIMPOR Souselas cement plant as the main source emitter, and the NAVIGATOR pulp and paper facility in Figueira da Foz as a possible backup supplier.

During the pilot phase, CO_2 would be captured from the identified sources and transported via railway and shipping for offshore injection. The pilot phase aims to inject up to 180 kt of CO_2 over three years, primarily sourced from the CIMPOR cement plant. The commercial phase will scale up the capture and transport infrastructure, including the construction of pipelines for continuous CO_2 transport. This phase aims to inject up to 0.5 Mt/year over a 30-year period, with the potential to expand to 4.7 Mt/year, to encompass further source emitters.

The pilot phase will use temporary infrastructure at the Figueira da Foz port, including loading/unloading facilities and onboard injection systems. The commercial phase will expand these facilities to include permanent infrastructure, such as high-pressure pumps, pipeline launch stations, and advanced safety and monitoring systems. These facilities are designed to handle increased CO_2 volumes and ensure long-term reliability and safety.

The cost structure for the project is detailed, with the pilot phase estimated to have a CAPEX of €72 million and an OPEX of €50 million over three years. The commercial phase is projected to have a CAPEX of €62 million and an OPEX of €338 million over 27 years. These costs include the construction and maintenance of transport and injection infrastructure defined for each phase, as well as the operational expenses associated with CO_2 handling and storage. The project aims to adopt the best strategies for efficient and cost-effective solutions, ensuring an efficient and affordable transition from pilot to commercial scale.

Ebro Basin (Spain):

The main objective for this deliverable is the design of surface facilities for the storage site, considering key engineering aspects and cost estimation. For that, some consideration and assumptions about capture, transport and CO_2 composition have been addressed.

Ebro basin selected scenario is based on a pre-commercial phase (pilot scale) and commercial phase with full life cycle. The project is planned to start a pilot phase or precommercial test phase, injecting 0.03 million tonnes of CO_2 per year for one year, followed by a commercial phase injecting 0.5 million tonnes per year. The storage capacity ranges from 2 to 26 million tonnes considering the uncertainties around the geological structure including compartmentalization and no-compartmentalization cases. Different potential CO_2 emitters have been identified -but none have been selected- and considered chemical absorption, which is cost-effective and flexible, for identified potential emitters. The expected capture cost is between 53 and 66 euros per tonne.

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.

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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.

It was assumed that CCS technology would be implemented in a pilot installation at a scale of up to 100 kt to attract investors and prove economic and technical viability, and then the pilot would be converted into a commercial installation. The CO_2 emitter has not been selected yet, but industry representatives who need to remove process emissions were considered: steelworks/steel mills, cement plants, chemical plants, large waste incineration plants will be CO_2 sources. During the pilot phase, road transport is considered the most likely, and after scale-up, transport by pipelines.

Macedonia Basin (Greece):

The Mesohellenic Basin (MHB) in West Macedonia, Greece, is a promising potential geological storage site for CO_2. Pentalofos and Eptachori Formations offer an estimated CO_2 storage capacity of 1.02–1.28 Gt and 0.13–0.17 Gt CO_2, respectively. Ptolemaida V, which is located in this region, is a CCS-ready power plant projected to emit up to 4.5 Mt CO_2 focusing on near-term capture scenarios. In previous years, it was anticipated that emitters near the MHB would emit up to 4.5 million tonnes of CO2 annually, however this has recently revised to a lower figure due to strong decarbonisation action implemented from the Greek Government. Significant emissions are still expected from nearby emitters due to the recent construction of the Ptolemaida V coal power plant, and the captured CO2 from the plant could potentially be injected into the MHB. The MHB, currently at Tier 1 development stage, presents a significant opportunity for Greece, as it combines strong storage potential, national decarbonisation goals, and the necessity for energy transition in former lignite areas. However, more detailed geological studies, infrastructure development, and a clear regulatory framework need to be promoted to support full-scale implementation.

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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, prioritization, and selection* (Canteli, 2023); D4.2 *Conceptual scenarios definition to enable decision support* (Canteli, 2024); D4.3 *Final concept description and preliminary consideration by regions* (Canteli, 2025b), and D4.9 *Economic evaluation of alternatives and prioritization results* (Canteli, 2025a), 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.

This deliverable identifies the capture technologies applicable to potential CO_2 source for each proposed pilot, the most feasible transport alternatives, and an outline of the potential CO_2 stream composition and specification from the source. Also, further defines the reception and injection facilities proposed in the previous deliverable D4.3 (Canteli, 2025b), based on current information availability.

Capture technology and transport opportunities will be outlined but not designed (as this task is out of the scope of this project) and their costs will be estimated.

A technical description of a scenario, in this context, refers to an overview of the elements to be built and the activities to be carried out over time to develop a pilot. The technical elements to be included (such as transport type, capture technology, surface facilities, injector wells, storage volumes, etc.) are aligned with the key decisions defined during the framing session and included in the scenario's definition. Given the level of uncertainty at this stage, it is only possible to provide a general overview. Subsequent phases of the study will offer increased detail, enabling the economic evaluation of the pilots.

4. CO_2 sources characterization

4.1 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. The outlet stream of the emitter is issued from a Steam Methane Reformer with a composition of 99% CO_2 and 1% H_2 (Canteli et al, 2025). The main source is associated with ammonia production plant process via natural gas reforming (Figure 1).

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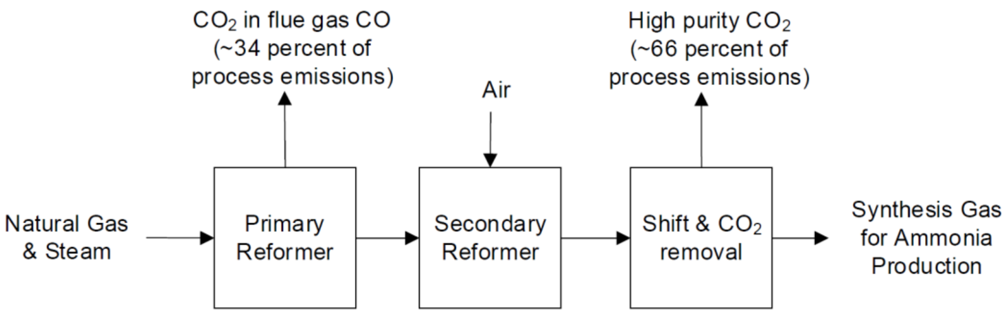
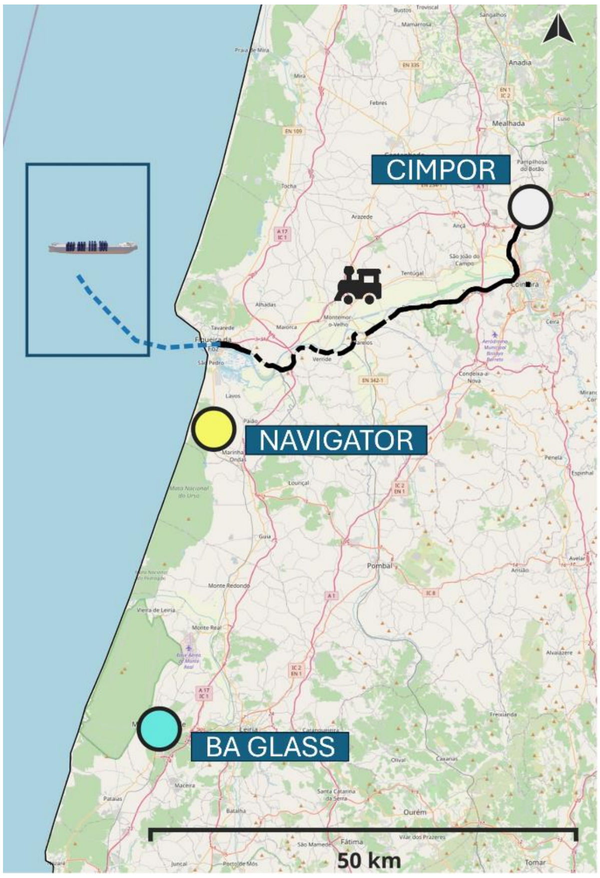


Figure 1 Amomnia production process (Hughes and Zoelle, 2022)

4.2 Lusitanian Basin (Portugal)

Portugal's effort towards carbon neutrality involves significant changes in the industrial sector, especially in sectors that are difficult to reduce emissions from, with cement production being a notable source of CO_2 emissions. During the pilot phase, the CIMPOR Souselas facility is identified as one of the major CO_2 sources due to its emission volume and proximity to the port of Figueira da Foz. In 2023, this facility emitted 0.8 Mt CO_2, representing 42.6% of CIMPOR's total emissions in Portugal. Clinker production, which is essential for cement manufacturing, is the most polluting part of the process. Currently, 79% of CIMPOR's cement consists of clinker, but the company plans to reduce this to 62.5% by 2030. CIMPOR is also following the roadmaps of ATIC and CEMBUREAU to achieve carbon neutrality by 2050, aiming to further decrease the clinker ratio to 60% by 2050. The primary source of emissions is the fuel burned in kilns. In 2023, 13.8% of biomass was used as fuel, but the company aims to increase this figure to 30% by 2030, amounting to 39.7 kg-CO_2/t clinker. According to the roadmap for achieving these targets, the facility will still emit 0.5 Mt of CO_2 in 2050, indicating significant potential for CCS. Besides direct emissions, process emissions such as calcination also contribute to CO_2 release. The roadmap includes using low or decarbonated raw materials to reduce impact, along with upgrading kilns to improve electrification, smart controls, and thermal efficiency. CIMPOR participated in the STRATEGY CCUS project and announced plans to develop a pilot capture facility.

Figure 2 Location of prospective CO2 sources for the pilot-scale phase



BA Glass facility in Marinha Grande, with 0.09 Mt of recorded emissions in 2023, represents 14.3% of all emissions from the glass industry in Portugal. During STRATEGY CCUS, dialogue with the glass sector singled out this BA GLASS factory as an early mover into CO_2 capture, with a capture

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pilot with a capacity of 0.03 Mt/yr. Glass industry has been evolving continuously, starting from wood and coal as the primary source of fuel to natural gas today. Following the improvement, the BA Glass facility is part of Nazaré Green Hydrogen Valley (NGHV) project and is implementing a green hydrogen plant in Marinha Grande, which will provide hydrogen to the facility by 2027. This transition is estimated to reduce direct emissions by 95%, resulting in only 0.002 Mt/yr CO_2 emissions by the year 2050. If the hydrogen strategy is not implemented in the facility, its emissions are forecasted to remain at 0.16 Mt/yr by 2050. **This path of emissions forecasted raised doubts about the economic feasibility of capturing such small amounts of emissions.** The facility is maintained as a possible source for the pilot-scale phase of PilotSTRATEGY given recent developments in technologies able to capture CO_2 from small sources, but estimates of volumes to inject or costs refer only to the CIMPOR Souselas cement factory.

Lastly, NAVIGATOR's pulp and paper facility in Figueira da Foz is regarded as an alternative source of CO_2 in case the CIMPOR pilot capture facility is not deployed in due time. Unlike the previously mentioned sources, the majority of emissions from NAVIGATOR are from biogenic origin. The facility has recently inaugurated a new biomass boiler and reduced the emissions by almost 30% in 2021. A total of 0.117 Mt and 1.61 Mt of CO_2 were emitted from fossil and biogenic sources respectively. Fossil fuels are mostly available as a backup and to maintain parameters in the boiler along with start-up and shut-down operations in these boilers with natural gas. NAVIGATOR has a plan of decarbonization approved by the *Science Based Targets initiative (SBTi)* aiming to achieve an 86% reduction of Scope 1 and 2 emissions by 2035 (w.r.t. 2018) along with shifting 80% of primary energy consumption to renewable sources. A clear business model for negative emissions from biogenic sources is still to be developed to compete with the utilisation of CO_2 for e-fuels. The potential of CO_2 use as a feedstock in e-fuels may lead to faster deployment of CO_2 capture at the NAVIGATOR facility at Figueira da Foz, and since small amounts are required for the PilotSTRATEGY pilot phase, this facility is considered as an alternative source of CO_2, provided a deal can be made with the company to supply CO_2.

Table 4.1 and Figure 2, depict the main information about the possible CO_2 sources as well as its location with respect to the Figueira da Foz port and the injection site.

FACILITY NAME & LOCATION	INDUSTRY	EU ETS PLANT ID	Distance from the port (km)	CO_2 Emissions (2023)	Emission forecast
CIMPOR – Souselas	Cement	174	55	0.69 Mt (fossil) 0.11 Mt (biogenic)	**By 2050:** 0.44 Mt (fossil) 0.06Mt (biogenic)
BA Glass – Marinha Grande	Glass	98	65	0.09 Mt (fossil)	**By 2050:** 0.002 Mt (fossil)
NAVIGATOR – Figueira da Foz	Pulp and Paper	291	30	0.11 Mt (fossil) 1.47 Mt (biogenic)	**By 2035:** 0.021 Mt (fossil) 1.79 (biogenic)

Table 4.1 Summary of selected emitters for the Lusitanian Basin project

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4.3 Ebro Basin (Spain)

Ebro basin development is based on a pilot case upgraded to commercial scale. It is not selected any specific emitter and a list of the closer *hard to abate* industries with higher annual emissions of 50.000 tonnes have been collected. The closer potential emitters are listed in the following Table 4.2:

Table 4.2 List of closer emitters to the planned injection site. GHG emission from 2015 to 2023 (https://prtr-es.es/)

FACILITY NAME	INDUSTRY	Distance from the port (km)	CO_2 Emissions (2015-2023 average)	Emission forecast
Saica 1	Paper and cardboard manufacturing	35	0.242 Mt (fossil)	**By 2050:** 0.250 Mt (total)
Saica Paper	Paper and cardboard manufacturing	14	0.410 Mt (fossil)	**By 2050:** 0.700 Mt (total)
Comercial Industrial Aries	Production of lime and plaster	25	0.061 Mt (fossil)	**By 2050:** 0.060 Mt (total)

Figure 3 shows the evolution of those emissions in the last years used for an estimation of the emissions forecast based on the trend during last 3 years and assuming keeping constant. It is not available at this stage the volume of biogenic CO_2 for each emitter.

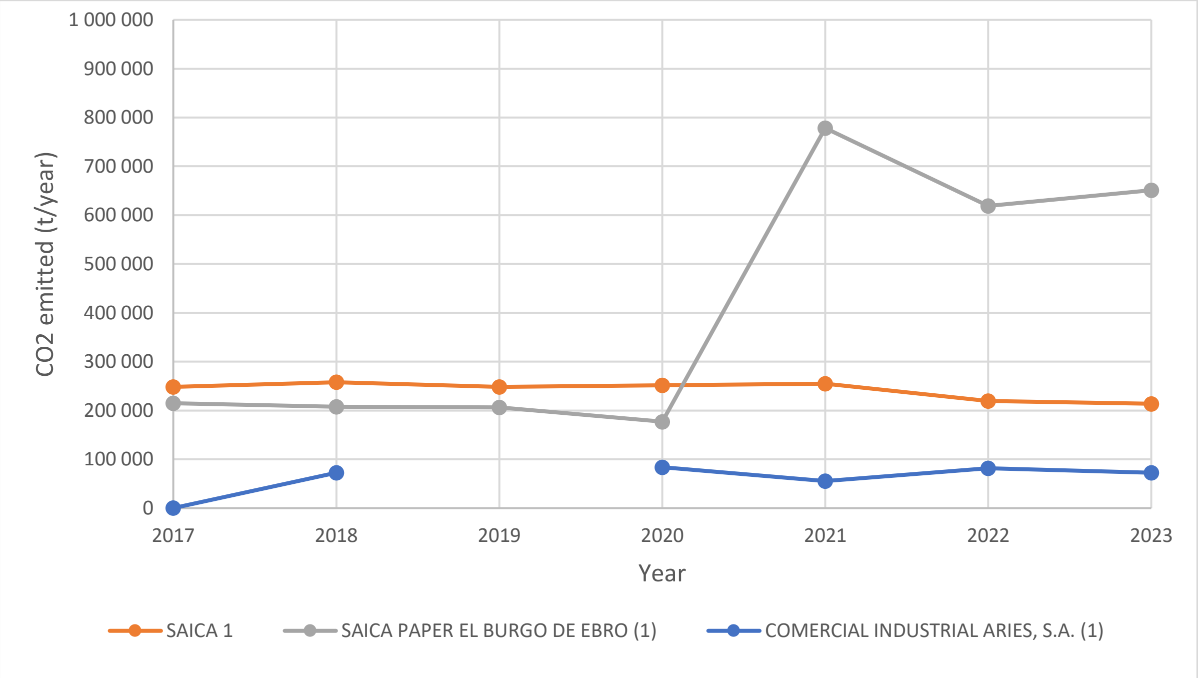

Figure 3 CO2 emissions of the previous table industrial complex in the last years. (1) means emitters that have reported emission of other gases that may content metals or other contaminants. (https://prtr-es.es/)

For further information about Ebro potential emitters see Deliverable 4.3 "Final concept description and preliminary consideration by regions" (Canteli, 2025b).

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4.4 Upper Silesia Basin (Poland)

For Upper Silesia, several emitters from cement industry, chemical plants, metal works and power plants are in a close area of potential storage sites selected, some of them with more than 1 Mt per year:

FACILITY NAME	Emission CO_2 (Mt/yr)	Year	Latitude	Longitude	Distance (km)
Rudniki Cement Plant	1.20	2022	50.8833	19.2833	29.55
Chemical Plant "Rudniki" S.A.	0.00025	2022	50.8833	19.2833	29.55
Małogoszcz Cement Plant	1.80	2022	50.8167	20.2667	41.42
Ironworks Częstochowa	0.70	2022	50.8286	19.1224	41.82
Heat and Power Plant Częstochowa	0.30	2022	50.7963	19.1224	42.82
Bełchatów Power Plant	38.30	2022	51.2481	19.3194	45.51
Lime Industry Plants "Trzuskawica" S.A.	0.00025	2022	50.8167	20.5667	62.02
Warta Cement Plant	1.50	2022	51.0186	18.8275	62.33
Kielce Heat and Power Plant	0.40	2022	50.8661	20.6281	65.54
Zinc Smelter "Miasteczko Śląskie"	0.50	2022	50.5583	18.9361	67.06
Ironworks Katowice (ArcelorMittal Poland)	5.50	2022	50.3350	19.1800	74.44
Tychy Heat and Power Plant	0.40	2022	50.1200	18.9900	101.93
Nitrogen Plants Kędzierzyn S.A.	1.20	2022	50.3500	18.2000	123.43
Bielsko-Biała Heat and Power Plant	0.50	2022	49.8225	19.0444	130.34
Górażdże Cement Plant	3.10	2022	50.4306	17.8000	144.78

Table 4.3 List of closer emitters to the planned injection site.

4.5 Macedonia Basin (Greece)

In terms of energy, West Macedonia has been Greece's energy hub since the 1950s, when lignite mining and power generation activities were first systematically developed, contributing to the electricity supply more than any other region. The area's emissions are dominated by a small number of large-scale industrial plants, most of which have been decommissioned or are in the process of being phased out according to the national decarbonisation strategy[1].

Five major power plants have been reported for nearly all CO_2 emissions in the Macedonia Basin, reaching a total of approximately 20.4 million tonnes per year in 2017. These include Agios Dimitrios, the largest coal plant in Greece, emitting around 9.5 Mt/year, followed by Kardia Power Plant and Amyntaio, with estimated emissions of 4.0 Mt/year and 3.5 Mt/year. The Power Plant of Meliti contributes approximately 1.2 Mt/year, while the older units of Ptolemaida (I-IV) collectively emit around 2.2 Mt/year. Moreover, a lime production facility in Amyntaio remains operational and emits a minor amount of CO_2 compared to other units (Carneiro, J.F., and Mesquita, P., 2020).

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

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Over the first ten months of 2023, Ptolemaida V, which is the most recently constructed power unit in West Macedonia, has emitted approximately 1.37 million tonnes of CO_2. In October 2023, Ptolemaida V accounted for 82.7% of all lignite-related CO_2 emissions, reflecting its current role as the primary lignite unit in operation at that time. Ptolemaida V commenced commercial operation in early 2023 and is currently scheduled to stop lignite combustion by 2026, with plans to convert to natural gas[2]. Table 4.4 summarises the key characteristics of these emissions sources.

Facility Name	Type	Estimated CO_2 Emissions	Status
Agios Dimitrios	Lignite Power Plant	~9.5 Mt/year	Decommissioning phase
Kardia	Lignite Power Plant	~4.0 Mt/year (historic)	Decommissioned
Amyntaio	Lignite Power Plant	~3.5 Mt/year (historic)	Decommissioned
Meliti	Lignite Power Plant	~1.2 Mt/year	Limited operation
Ptolemaida (I-IV)	Lignite Power Plants	Combined ~2.2 Mt/year	Decommissioned
Ptolemaida V	Lignite Power Plant (CCS-ready)	~4.5 Mt/year (projected)	Operational
Amyntaio Lime Plant	Lime Production	~0.04 Mt/year (40 kt/year)	Operational

Table 4.4 Industrial Plants in West Macedonia and their estimated CO_2 emissions

5. Capture technology applicable by regions

5.1 Available technologies worldwide

The technology selected to capture CO_2 from a feed stream is generally determined by the feed stream properties and components, alongside considerations of energy, cost, and utility availability. The primary technologies used for CO_2 capture are absorption, adsorption, membrane and cryogenics. Other technologies as solid looping, inherent capture, Direct Air Capture and others are in different degrees of development.

As of today, the principal available technologies for capture of CO_2 from different industrial sources are listed and briefly explained below:

5.1.1 Absorption technologies

In an absorption process, CO_2 gas is dissolved into a liquid solvent to form a solution. This solution can then be transported to a different section of the plant to allow for the regeneration of the solvent and the release of the CO_2 from the liquid.

There are two forms of solvents used in absorption CO_2 capture: chemical and physical. Chemical solvents have reactive components that enter into a chemical bond with CO_2 to transport it to the desorber, where heat is usually applied to break the bond and release the CO_2.

Physical absorbents rely on the dissolution of CO_2 into the solvent through physical drivers such as pressure, and CO_2 is held by molecular forces.

[2] The carbon footprint of electricity production-October 2023 (www.thegreentank.gr)

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Chemical absorbents tend to be more suitable for streams with lower CO_2 partial pressures, while physical absorbents tend to be more suitable for streams with higher CO_2 partial pressures.

This technology can be retrofitted to existing power plants and industrial facilities, making it a versatile option.

Post-combustion capture using amine-based solvents typically achieves around 85-90% CO_2 capture efficiency. However, it requires significant energy for solvent regeneration, which can reduce the overall efficiency of the process.

5.1.2 Adsorbent technologies

Adsorbents are solid materials that have binding sites on the surface of the sorbent to remove CO_2 preferentially from a gas stream. The materials generally have either a porous surface or granular structure that develops a large surface area and many potential binding sites to capture CO_2.

Also, chemical and physical adsorption methods are available.

When the binding sites are fully occupied, the CO_2 can be released by either a reduction in pressure or increase in temperature. This swing in conditions will change the driving force of the environment to unbind CO_2 from the solid adsorbent, resulting in a higher concentration stream released from the adsorbent bed for further processing.

Adsorption technologies can achieve CO_2 capture efficiencies of 85-95%. They offer lower energy consumption compared to solvent-based methods but require frequent regeneration of the adsorbent material.

5.1.3 Membrane Separation

A membrane is a semi-permeable barrier or medium that can separate particular chemical constituents of a gas mixture based on their relative rates of mass transfer through the barrier or medium. For CO_2 capture plants, CO_2 would pass through the semi-permeable membrane the quickest compared with other molecules in the gas stream (Drioli *et al.*, 2018). Membrane separation primarily uses the partial pressure of CO_2 and the overall pressure of the inlet gas to drive the separation of CO_2 from the feed gas stream. Membrane separation is generally more favourable when there are higher partial pressures of CO_2 in the feed gas stream, and a higher overall inlet gas stream pressure to drive the movement of CO_2 across the barrier.

These membranes can be made from various materials, including polymers and ceramics, and are used in both pre- and post-combustion capture processes. Membrane separation is a compact and modular technology that can be easily integrated into existing systems. It requires less energy than traditional solvent-based methods but may have lower CO_2 capture efficiency. Advances in membrane materials and designs are improving its performance and cost-effectiveness.

Membrane separation technologies typically achieve CO_2 capture efficiencies of 80-90%.

5.1.4 Cryogenic distillation

Cryogenic distillation involves cooling the flue gas to very low temperatures to condense and separate CO_2 from other gases. This method is energy-intensive but can be effective for high-purity CO_2 capture. It is commonly used in industries where low-temperature processes are already in place, such as natural gas processing and liquefied natural gas (LNG) production. This process generates liquid CO_2

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as a part of the production process without further treatment; other CO_2 processing facilities that need to make liquid CO_2 for transport by road, rail, or ship will have a small cryogenic liquefaction unit after the main CO_2 capture facility.

Cryogenic distillation can achieve high CO_2 recovery rates but requires significant capital investment and operational costs. Also, this technology can achieve high CO_2 capture efficiencies of up to 99%. However, it is very energy-intensive due to the need for cooling gases to extremely low temperatures.

5.1.5 Others

Some new capture technologies are still in research, development or demonstration stages and could provide additional methods for capturing CO_2 from different source types in an efficient and profitable manner. These potential technologies include:

- **Inherent Capture:** Inherent capture technologies or process refer to systems that produce high partial pressure CO_2 as an inherent part of the process. This stream of higher partial pressure CO_2 generally requires little to no additional work or energy to separate CO_2. Some chemical processes already inherently produce high partial pressure, high concentration CO_2 to make the desired chemical. This includes the fermentation of ethanol and the production of ethylene oxide. Extracting CO_2 from the process stream of hydrogen to produce ammonia also produces a high partial pressure of CO_2, though it tends also to contain other components.

- **Solid Looping technologies:** A solid looping capture process involves the use of a metal oxide (MeO) or other solid regenerable compound such as metal carbonates ($MeCO_3$) that can carry CO_2 from a carbonator reactor to a calciner reactor.

  This process produces a stream of CO_2 and water vapor, which can be easily separated. The metal oxide is then regenerated by reacting with air, completing the loop. Chemical Looping Combustion offers high efficiency and low energy penalties for CO_2 capture.

  A capture plant with this technology is currently under construction in Texas (US).

- **Oxy-Fuel Combustion:** Oxy-fuel combustion burns fossil fuels in pure oxygen instead of air, resulting in a flue gas that is mainly CO_2 and water vapor. The water vapor is condensed, leaving a concentrated stream of CO_2 that can be easily captured. This method reduces the volume of flue gas and simplifies CO_2 separation.

- **Direct Air Capture:** Direct Air Capture (DAC) technologies capture CO_2 directly from the ambient air using chemical reactions. The captured CO_2 can then be stored underground or used in various industrial applications, such as synthetic fuels or carbonated beverages. DAC is particularly useful for offsetting emissions from dispersed sources, such as transportation. However, it requires large amounts of energy and is currently more expensive than other capture methods. Research is ongoing to improve its efficiency and reduce costs.

- **Biological capture:** Biological methods use microorganisms or algae to capture CO_2 through photosynthesis. The captured CO_2 is converted into biomass, which can be used as a biofuel or for other purposes. Algae cultivation systems, such as photobioreactors, can be integrated with industrial facilities to capture CO_2 emissions. Biological capture is a sustainable and environmentally friendly approach but requires large areas of land and water resources.

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- **Mineralization:** Mineralization involves reacting CO_2 with naturally occurring minerals to form stable carbonates. This method can be used for both capturing CO_2 and storing it permanently. Mineralization processes can occur naturally or be accelerated through industrial methods. It offers a permanent and safe solution for CO_2 storage but requires significant amounts of minerals and energy.

- **Electrolysis of ocean water:** currently some field trials are ongoing.

5.2 Cost estimation outline

Capture cost factors primarily relate to the properties of the stream from which the CO_2 is separated. This includes the concentration of CO_2 in the stream, the pressure, and the overall volume of CO_2 to be captured. Economies of scale especially play a role in CCS projects, where capital costs can be very significant. The underlying technology used to capture CO_2, as well as the targeted CO_2 capture percentage, energy and cooling costs, plant location and any necessary pre-treatment of the inlet stream to the capture plant, all have an impact on the overall cost to capture CO_2 (Global CCS Institute, 2025).

The expected cost ranges of CO_2 captured shown in the next table (Table 5.1) are the total annualized cost of a CO_2 capture plant (Capital + Operational cost) divided by the total annualized CO_2 volume captured by the plant (the output CO_2 stream).

Source	Levelised cost range (EUR/tonne CO_2)	Comment
Absorption	13.2-66	Cost includes the costs of solvent regeneration and energy consumption, which are significant.
Membrane separation	26.4-52.8	The cost depends on the type of membrane used and the specific application.
Cryogenic distillation	66.1-132.1	The high energy consumption required for cooling gases to very low temperatures contributes to the overall cost.
Adsorption	17.6-44	These costs include the price of adsorbent materials and the energy required for regeneration
Direct Air Capture (DAC)	>176	Efforts are ongoing to reduce these costs to below $200 per tonne to make DAC more economically viable.

Table 5.1 Levelized cost ranges for CCS capture for different technologies

5.3 Paris Basin (France)

As indicated above (section 4.1), the French case is based on an outlet stream from a Steam Methane Reformer with a composition of 99% CO_2 and 1% H_2 (Canteli et al, 2025). Consequently, no additional capture equipment is required.

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5.4 Lusitanian Basin (Portugal)

A wide range of technologies are available in the market for CO_2 capture; however, not all are at commercial readiness for different industries. The Global CCS Institute has assessed the readiness of these technologies and scored them out of 10, Table 5.2 presents the highest-rated technologies. Although defining the capture technologies that the facilities will install is outside the scope of PilotSTRATEGY, since it requires a detailed assessment of the conditions and feasible at each installation, the cement industry is clearly moving into the Chemical Absorption technologies, while Calcium Looping is also being considered. Studies for the glass and pulp & paper industry have pointed to the same technologies, although these sectors have been far less engaged in defining selecting suitable capture technologies than the cement sector.

CATEGORY	TECHNOLOGY	READINESS ASSESSMENT
Chemical Absorption	Amine based Solvents	9
	Hot Potassium Carbonate (HPC)	9
	Sterically hindered amine	6-9
Physical Absorption	Physical Solvents	9
Solid Adsorbent	Pressure Swing Adsorption/Vacuum Swing Adsorption	9
Membrane	Gas separation membranes for natural gas processing	9
Cryogenic Separation	Cryogenic Distillation	9

Table 5.2 CCS Technology with highest readiness level in 2024 out of 10

Amine based solvents, a Chemical Absorption technology, is widely studied, mainly due to availability of extensive literature and its non-proprietary nature. One of the benefits of this technology is the flexibility it has for the concentration of CO_2 in flue gas. These amine-based capture systems use chemical solvent to trap the CO_2 in the flue gases, with MEA (Monoethanolamine) as the most widely used solvent due to its rapid reaction rate, lower costs and weight. As illustrated in Figure 4, the flue gas is first passed through a chamber where CO_2 is absorbed in amines (Absorber unit), this CO_2 rich aqueous MEA solution is than heated in another column, the Desorber unit, where the CO_2 is separated due to heat from the rich solution. The lean MEA solution is recycled back in the system and clean CO_2 free gas is emitted from the Absorber unit. The separated CO_2 from Desorber unit is compressed for transportation/storage.

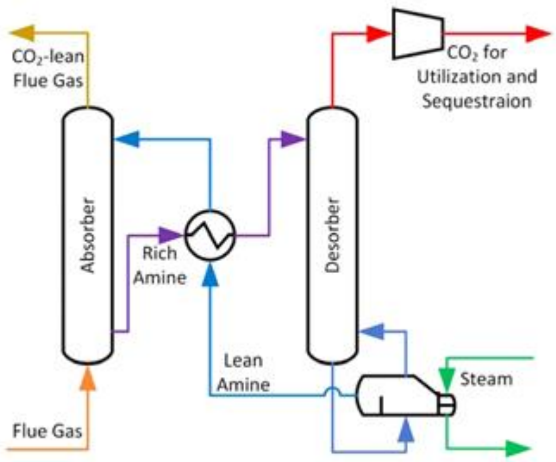

Figure 4 Schematic of MEA based Chemical Absorption CCS unit.

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5.4.1 Outline capture cost

The applicability of the technology is hugely impacted by the total upfront and recurring costs that it comes with. In industries, the composition and pressure of the flue gas varies, so that the average cost in €/t_{CO2} of CO_2 capture varies accordingly. Just like any industrial plant, the initial capital cost of the CO_2 capture plant does not scale proportionally solely based on the increased capture capacity, but on an average, for selected industries, a more probable range is between **50-70 EUR/t_{CO2}** as adapted from the Figure 5. Nonetheless, this is a reference value, and the actual capture can only be estimated with a detailed design of the capture facility in each of the three likely emission facilities, which is beyond the scope of PilotSTRATEGY.

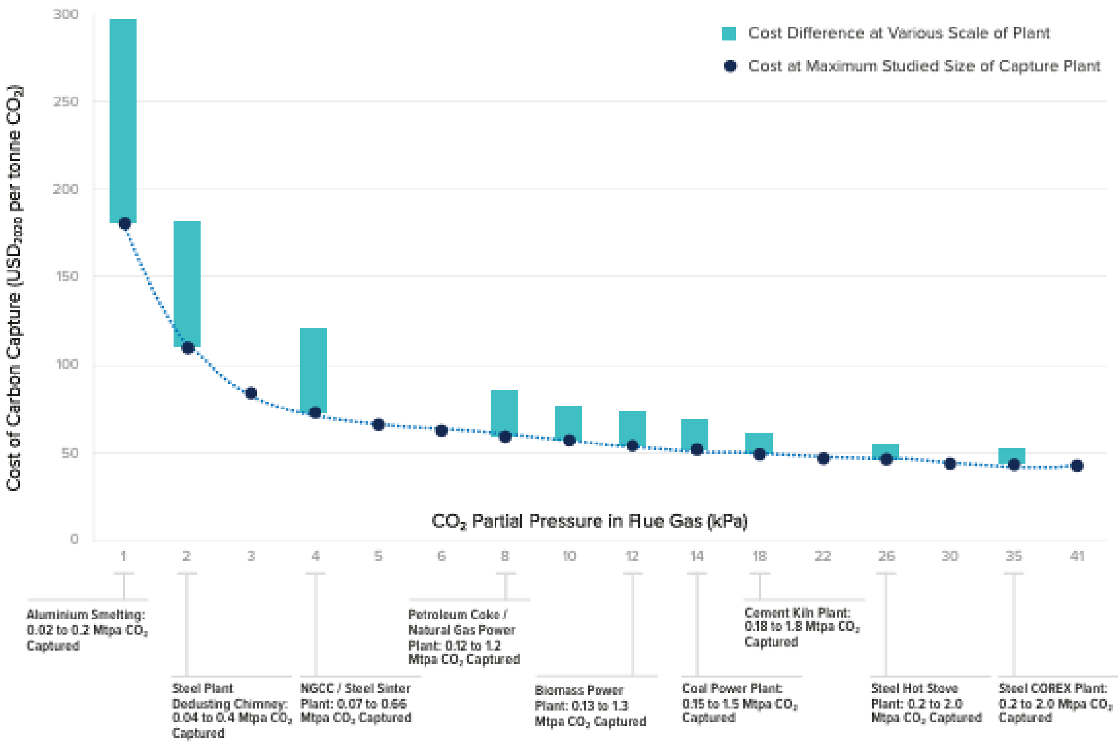

Figure 5 Cost of Carbon Capture System based on industry type and CO2 partial pressure in flue Gas

5.5 Ebro Basin (Spain)

5.5.1 Ebro capture concept and capture cost outline

For capturing the CO_2 coming from the potential sources for Ebro region project, chemical absorption option is considered the best option as it is currently the more mature technology with the most competitive costs and flexible and versatile applications.

Usual MEA (chemical solvent) CO_2 capture facilities are modelled with a twin-column arrangement that exchanges solvent that is "rich" and "lean" in CO_2 between the columns. The absorber column is where CO_2 is separated from a gas stream by a reaction with MEA to form a "rich solvent". This solvent is then transferred to the desorber column, where heat is used to separate MEA and CO_2. "Lean solvent" is recovered from the bottom of the desorber, which is then recycled for use again in the absorber.

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The process schematic flow diagram, as well as the ancillary units to be used, are outlined (Figure 6).

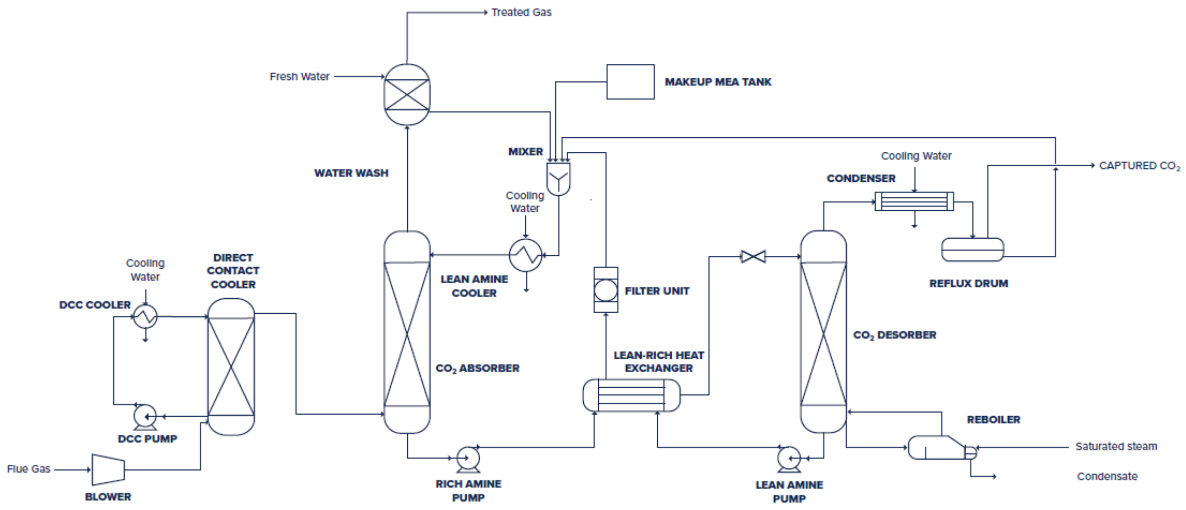

Figure 6 Ebro capture process proposal scheme

Due to the low-medium size of the Ebro project (0.5 Mtpa during the commercial phase), no economies of scale could be leveraged, and the expected range of total levelized capture cost for the Ebro project will be in the highest quartile: **53-66 EUR/t_{CO2}**

5.6 Upper Silesia Basin (Poland)

Based on a review of carbon capture technologies and considering the industrial profile of Silesia, Poland, the following recommendations are proposed for implementing CO_2 capture systems in various types of industrial facilities. This strategy addresses technology suitability, gas stream characteristics, technical challenges, and potential technology providers.

- Coal and Biomass Power Plants (Tauron, PGE Rybnik, Bełchatów (lignite), Enea Połaniec (biomass/coal blend))
  - Technology: Post-combustion with amines (MEA, MDEA)
  - Cost Range: 35–80 EUR per tonne of CO_2 avoided
  - Drivers: Flue gas treatment, energy for solvent regeneration, scale of integration
- Cement Plants (Holcim Małogoszcz, Cemex Rudniki, Górażdże, Warta, Dyckerhoff)
  - Technology Options: Post-combustion, oxy-fuel combustion, calcium looping
  - Cost Range: 45–115 EUR per tonne of CO_2
  - Factors: Dust interference, kiln integration complexity, process energy recovery potential
- Chemical Plants (Synthos (rubber/chemicals), Grupa Azoty (fertilizers))
  - Technology: Process-integrated separation, membranes, PSA, amine scrubbing
  - Cost Range: 25–70 EUR per ton CO_2 (high-purity CO_2 streams lower cost)
  - Variables: Process-specific gas compositions, integration complexity
- Steel and Metallurgical Plants (ArcelorMittal Dąbrowa Górnicza)
  - Technology: Off-gas separation, pre-combustion capture (where applicable)
  - Cost Range: 60–130 EUR per tonne of CO_2

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- Constraints: Mixed gas streams (CO, CO_2, H_2), high temperatures, blast furnace integration
- Waste-to-Energy and Incineration (Regional incinerators, e.g. Katowice, Kraków vicinity)
  - Technology: Post-combustion with amines or solid sorbents
  - Cost Range: 53–100 per tonne of CO_2
  - Factors: Fluctuating waste composition, oxygen-rich gases, need for high-selectivity capture

5.7 Macedonia Basin (Greece)

Ptolemaida V has been built with CCS readiness, and it has a gross capacity of 660 MW and is expected to emit up to 4.5 million tonnes of CO_2 per year during full lignite-based operation (Coussy, P., 2020). The plant started its commercial operation in 2023 and is scheduled to transition from lignite to natural gas by 2028, which is still require CO_2 capture solutions due to EU carbon pricing policies (Carneiro, J.F., and Mesquita, P., 2020).

Two main scenarios have already developed to evaluate CO_2 capture deployment in Mesohellenic Basin in West Macedonia, tailored to short-and long-term timelines:

Scenario A: Short-to Medium-term (2030)
The short-term scenario focusing on deploying capture technology at Ptolemaida V, which will be the only significant remaining CO_2 source at post-lignite phase-out. The capture volume has estimated to ~4.5 Mt CO_2/year, thus it is a major target for capture interventions. The scenario assumes the use of commercially available technologies (e.g. amine-based post-combustion capture systems) that are mature and widely applied in similar contexts. Besides aiming Greece to achieve its climate goals, installing capture technologies at Ptolemaida V also contributes to supporting the regional workforce. The captured CO2 is planned to be transported and injected into suitable geological formations within the Mesohellenic Basin, which is located in close proximity to CO_2 sources and offers substantial storage potential (Koukouzas et al., 2021).

Scenario B: Long-term (2050)
The long-term scenario, looking forward to 2050, aims the full integration of CCUS as a reliable solution for managing residual emissions within a near-zero carbon energy system. Although the capture activities may broaden and include emerging sources such as hydrogen production or new industrial emitters, the total volume of CO_2 is expected to be lower than in 2030. This is due to augmented electrification and structural changes in the sectors of energy and industry. According to this scenario, the captured CO_2 could be directed partly toward geological storage in the Pentalofos and Eptachori formations of Mesohellenic Basin, and partly toward utilisation pathways (e.g. production of construction materials or synthetic fuels). Moreover, this long-term case promotes the potential for cross-border cooperation, allowing West Macedonia to participate or serve as a hub for wider CO_2 collection and storage networks throughout Balkans and Southeastern Europe (Koukouzas et al., 2021).

The Mesohellenic Basin has been identified as a candidate for CO_2 storage, based on its size, geology, and proximity to main emitters. Two key formations have been assessed (Table 5.3) (Koukouzas et al., 2021):

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Formation	Main Lithology	Estimated Storage Capacity	Porosity
Pentalofos	Conglomerates, turbiditic sandstones, shales	~1.02–1.28 Gt CO_2	7–25%
Eptachori	Marine shales, sandstones, conglomerates	~0.13–0.17 Gt CO_2	~15% porosity

Table 5.3 Lithology, Storage Capacity, and Porosity of Geological Formations in the Mesohellenic Basin

Additional storage potential is under consideration in the Grevena Sub-Basin; however, its capacity is expected to be more limited and currently is pending field investigation.

The Mesohellenic Basin is currently at a Tier 1 maturity level for CO_2 storage, as it is still in conceptual phase. Reaching to operational status will demand a detailed geological characterisation accompanied with seismic surveys, while injectivity and caprock should undergo integrity tests. The development of clear permitting procedures, monitoring systems and comprehensive risk management frameworks are also required, ensuring the safety and effectiveness of the implementation. However, no pilot injection has occurred until now, and regulatory procedure in Greece remain in early stages. However, significant progress has been achieved under PilotSTRATEGY project where a detailed geological mapping with sample collection and laboratory investigation have shed light on the potential of MHB as a CO2 storage area. One of the main findings resulted from the area is the ideal rock capping properties that the area possesses with minimal permeability and close to zero porosity (Tyrologou, 2023)

6. CO_2 stream quality specification

European Commission CCS Directive emphasizes the need to impose constraints on the composition of CO_2 streams to ensure safe geological storage, isolating CO_2 emissions from the atmosphere and minimising risks to transport and storage networks, the environment, and human health.

Directive outlines three key requirements for CO_2 streams:

1. CO_2 streams must be predominantly carbon dioxide.
2. Waste or other matter cannot be added for disposal purposes.
3. CO_2 streams may contain incidental substances from the emission source, capture, or injection processes, and trace substances for monitoring CO_2 migration, but these must not compromise storage site integrity, pose significant risks, or breach EU legislation.

Member States of EU must ensure operators analyse CO_2 stream composition, assess risks, and maintain a register of CO_2 streams delivered and injected, including their properties and composition. Enhanced CO_2 concentrations in ambient air can impact human health and the environment.

A CO_2 stream, resulting from CO_2 capture processes, must predominantly consist of carbon dioxide. The concentration of CO_2 and other substances in the stream can impact human health and the environment. Competent authorities must balance the cost of purifying CO_2 streams with managing associated risks.

Key aspects are:

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- No waste or other matter can be added to the CO_2 stream for disposal.
- Additional substances may be allowed if necessary for safe geological storage, provided they do not compromise storage integrity or pose significant risks.
- Mineralization projects, where CO_2 is dissolved in water and stored, are permissible.
- Acceptable levels of non-CO_2 constituents must comply with relevant EU legislation and be assessed for risks to storage site integrity, transport infrastructure, and human health.
- Operators must analyse CO_2 stream composition, conduct risk assessments, and maintain records of CO_2 streams delivered and injected.

Risk assessments should consider variations in CO_2 stream composition and the potential impacts of different constituents, including those that affect corrosion, human safety, and physical properties of the CO_2 stream. Operators and authorities should optimize CO_2 stream composition across the capture, transport, and storage chain, and take corrective measures for any irregularities.

6.1 Paris Basin (France)

As indicated above (section 4.1), the French case is based on an outlet stream from a Steam Methane Reformer with a composition of 99% CO_2 and 1% H_2 (Canteli et al, 2025). Consequently, no additional capture equipment is required.

6.2 Lusitanian Basin (Portugal)

6.2.1 CO_2 Stream Quality Specifications

The CO_2 stream quality specifications are crucial for ensuring the safe and efficient transport and storage of CO_2. The flue gas composition from the three potential CO_2 sources for the pilot will be inherently different, and it is likely that for the pilot phase of the project, given the minimal amounts of CO_2 to be injected, the admissible stream quality is adjusted to minimize costs of purification from the selected source(s). The commercial phase will follow the CO_2 quality ISO standards ISO-27913 or any standards that will be adopted or recommended by the EC by the time the storage project reaches commercial scale.

Still, given the lack of formal commitment of any of the CO_2 sources and the impossibility to define an admissible CO_2 quality for the pilot phase, it was decided to adopt the same composition for the CO_2 stream for the pilot and the commercial phase, and similar to those adopted for the Porthos project, with which the Lusitanian basin case study has several similarities. Thus, the following specifications were defined both phases of the project, bearing in mind that ISO-27913 or future standards that may be recommended by the EC will gain prevalence.

6.2.1.1 Purity

The CO_2 stream must have a high purity level to prevent contamination and ensure efficient storage. Impurities such as nitrogen, oxygen, and sulfur compounds should be minimized. The fluid composition considered for the Lusitanian Basin CCS project is based on the specification adopted by the Porthos project (Table 6.1).

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Component	Concentration	Notes
CO_2	≥ 95%	
H_2O	≤ 70 ppm	To avoid hydrate formation topside and corrosion due to free water
Sum of H_2, N_2, Ar, CH_4, CO, O_2	≤ 4%	
H_2	≤ 0.75%	Scope to increase this limit if valuable, up to 2% seen in some projects
N_2	≤ 2.4%	
Ar	≤ 0.4%	
CH_4	≤ 1%	
CO	≤ 750 ppm	
O_2	≤ 40 ppm	Limited to minimize risk of chemical reactions
Total sulphur-containing compounds (COS, DMS, H_2S, SOx, Mercaptan)	≤ 20 ppm	
H_2S		Toxic in case of release, corrosive when dissolved in water (lowers pH), reduces H_2O solubility
SOx		Lowers pH, corrosive when dissolved in water, promotes $FeSO_3.3H_2O$ formation
COS		Possible source of S, intermediate between CO_2 and CS_2, can hydrolyze in the presence of water forming H_2S and CO_2
Total NOx	≤ 5 ppm	Limited to minimize risk of chemical reactions
Total aliphatic hydrocarbons (C_2 to C_{10})	≤ 1200 ppm	To avoid/limit liquid hydrocarbon phase
Total aromatic hydrocarbons (C_6 to C_{10}, including BTEX)	≤ 0.1 ppm	To avoid/limit liquid hydrocarbon phase

Table 6.1 Porthos Project Specification Summary

This composition is valid for pipeline cases and for transport to shipping, but also for storage. Additionally, a representative fluid composition for pipeline design has been created, considering worst-case scenarios and again based on the Porthos project (Table 6.2).

Component	Amount (mol%)
CO_2	96
Methane	0,1
CO	0,5
H_2	0,75
N_2	2,0
O_2	0,645
H_2S	0,002
Ethane	0,003

Table 6.2 Composition used for project based on Porthos specification

A composition with low purity 96 mol% CO_2 and a maximum of 0.75 mol% H_2, along with a range of other impurities, allows for conservative application of operability and safety engineering principles.

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Future work should focus on assessing the cost-effectiveness of pre-transport impurity removal compared to transporting a fluid close to Porthos' maximum limits.

- **Pressure and Temperature**

The rationale for estimating the properties of CO_2 at various phases of its capture, transport, and storage is based on maintaining its optimal state for efficiency and safety (Table 6.3). During the capture phase, CO_2 is typically in a gaseous state at low pressure and moderate temperature, suitable for initial separation from industrial processes. For railway transport, CO_2 is then converted to a medium pressure and low temperature (dense phase) to ensure stability and compactness for efficient tank transportation. When shipping CO_2, currently available options suggest it should be maintained in a dense phase at medium pressure, facilitating large-scale transport. Nevertheless, CO_2 should pass through an injection pump before being injected into the reservoir. For offshore pipeline transport, CO_2 received by the local sources should be kept in a dense or supercritical state at high pressure and moderate temperature, before being injected. CO_2 injected into the reservoir at significant depth would be at high pressure and in a dense/supercritical state to optimize storage capacity while assuring reservoir stability.

Phase	Pressure	Temperature	State of CO_2
Capture*	1 – 2 bar	40 – 60°C	Gas
Railway	15 bar	-28°C	MP Dense
Shipping	15 bar	-28°C	MP Dense
Offshore Pipeline	120 – 140 bar	Inlet temperature of 50°C	Dense/Supercritical
Injection/Storage *(ca. 1200 m depth)*	120 – 140 bar	40 – 50°C (reservoir)	Dense/Supercritical

Table 6.3 Pressure and Temperature properties considered for each transport phase (Pilot and Commercial phases). Temperature and Pressure properties at the capture phase would be compressed into a medium pressure dense phase before onshore transport to the port.

The CO_2 stream quality specifications for the Lusitanian Basin are designed to ensure the safe and efficient storage of CO_2. These specifications include high purity levels, optimal pressure and temperature conditions, and robust containment and injectivity measures.

- **Shipping Design Conditions (Pilot Phase)**

There are several challenges for shipping transport, considering ~90 kt/year CO_2 injection for 3 years. These include:

  - **Pressure Management**: The recommended shipping pressure of 70 bar exceeds the current CCS industry practice of 40 bar. This higher pressure (HP) may pose operational challenges and increase shipping and storage costs, and that is the reason why medium pressure (MP) (15 bar) should apply in this case
  - **Vessel Supply**: The availability of HP shipping vessels capable of operating at 70 bar may impact the project schedule. The supply chain for such specialized vessels is limited, which could lead to delays, and that is why it would be required MP shipping (solutions found in the market estimate about 15 bar at low temperature)

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- **CO_2 Purity**: Current CCS industry practices assume very high purity CO_2 (>99.7 mol%). Ensuring this level of purity may require additional processing and quality control measures

- **Pipeline Design Conditions (Commercial Phase)**

After the Pilot phase, the design conditions for CO_2 transport should be estimated, considering the fluid properties, to ensure dense phase flow during injection.

The average inlet flowrate for CO_2 injection is calculated based on the annual storage rate and the system uptime. The industry standard recommends a system uptime of 95%, which accounts for maintenance and unexpected shutdowns. The mass flowrate can be calculated using the formula:

$$Mass\ Flowrate = \frac{\text{Annual Storage Rate}}{\text{System Uptime x Seconds per Year}}$$

Given the Annual Storage Rate of *ca*. 0,5 Mt (500,000 tonnes), a System Uptime of 95% and 31,536,000 seconds/year, the Mass Flowrate would be calculated as follows:

$$Mass\ Flowrate = \frac{\text{500,000 tonnes/year}}{\text{0,95 x 31,536,000}} = 16{,}76\ kg/s$$

The pressure conditions for the pipeline are maintained at a maximum inlet pressure of 140 bar to ensure safe margins of operation, while the temperature is expected to be around 50°C. These conditions ensure that CO_2 remains in a dense phase, optimizing transport efficiency and safety.

6.3 Ebro Basin (Spain)

CO_2 specification is based on ISO-27913 “Carbon Dioxide capture, transportation and geological storage - Pipeline transportation systems”. 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 (Table 6.4).

As HYSYS 14 was the process simulation software used for the facilities simulation, a dummy CO_2 composition was assumed based on the relevant ISO standard, considering only the most significant impurities that can impact hydraulic calculations. Although more accurate Equations of State (EoS) such as Cubic-Plus-Association (CPA) and GERG are generally recommended for modeling CO_2-rich streams, the Peng-Robinson (PR) EoS was selected in this case as it provides more conservative results for equipment and pipeline sizing. Only components relevant for hydraulic behavior were included to ensure meaningful and practical simulation outcomes. The final CO_2 composition used for the HYSYS modeling is presented in the following table (Table 6.5).

Ebro Region project specification can be compared to those from important CCS projects in UE as Aramis (the Netherlands, currently under construction) or Northern Lights (operative). In the following Table 6.6, threshold figures for main different components in the mentioned projects are shown and compared with Ebro specification proposed.

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<table>
<tr><th>Species</th><th colspan="3">Indicative levels (volumetric composition in ppmv, unless stated as mol%)</th></tr>
<tr><td>CO_2</td><td colspan="3">>95 mol%[a]</td></tr>
<tr><td>H_2O</td><td colspan="2">Corrosion, 20 to 630[b], Hydrate, <200[c,d]</td><td rowspan="10">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.</td></tr>
<tr><td>H_2</td><td><0,75 mol%[e,f]</td><td rowspan="6"><4 % total for all non-condensable gasses, but individual contributions may also be significant</td></tr>
<tr><td>N_2</td><td><2 mol%[f,g]</td></tr>
<tr><td>Ar</td><td>[f]</td></tr>
<tr><td>CH_4</td><td>[f,g]</td></tr>
<tr><td>CO</td><td><0,2 mol%[j,k]</td></tr>
<tr><td>O_2</td><td>[f,h]NB. Downstream limitations</td></tr>
<tr><td>H_2S</td><td><200[g,i,k]</td><td rowspan="3">Individual values, each below STEL,[m] but see Footnote n.</td></tr>
<tr><td>SO_2</td><td>Health and Safety < 100[k,l]</td></tr>
<tr><td>NO_2</td><td>Corrosion < 50[n]</td></tr>
<tr><td>Amine</td><td></td><td colspan="2" rowspan="4">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).</td></tr>
<tr><td>Methanol</td><td></td></tr>
<tr><td>Ethanol</td><td></td></tr>
<tr><td>Glycol</td><td></td></tr>
<tr><td>C_2+</td><td colspan="3"><2,5 mol%[o]</td></tr>
</table>

Table 6.4 ISO-27913 table A.1 composition standards for CO2 pipeline transport

Element	Mole Fraction	ppm	%
CO2	0,9666	966600	96,66
H2O	0,0001	100	0,01
Oxigen	0,0001	100	0,01
Nitrogen	0,0200	20000	2,00
Methane	0,0100	10000	1,00
Hydrogen	0,0010	1000	0,10
Argon	0,0010	1000	0,10
CO	0,0005	500	0,05
Ethane	0,0001	100	0,01
Propane	0,0001	100	0,01
Methanol	0,0005	500	0,05
Total	1,0000	1000000	100,00

Table 6.5 Final CO2 composition used for HYSYS modelling

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Class	Component	Constraint	unit	Ebro project	Aramis spec (Pipeline)	Northern Lights (shippping spec)
	CO_2	larger than	mol%	95.0	95.0	99.8
	H_2O	less than	ppmmol	100	70	30
inerts	N_2	less than	mol%	2.0	2.4	<0.05
	O_2	less than	ppmmol	100	40	10
	H_2	less than	ppmmol	1000	7500	50
	Ar	less than	mol%	0.1	0.4	<0.1
	CH_4	less than	mol%	1	1	<0.1
	CO	less than	ppmmol	500	750	100
	$O_2+N_2+H_2+Ar+CH_4+CO$	sum less than	mol%	3.5	4.0	-
	NO_x	sum less than	ppmmol	-	2.5	<1.5
sulphur	H_2S + COS + SO_x + DMS	sum less than	ppmmol	-	20	10
Volatile organic components	Total volatile organic compounds (excl. MeOH, EtOH, aldehydes)	sum less than	ppmmol	-	10	10
	Methanol	less than	ppmmol	500	620	30
	Ethanol	less than	ppmmol	-	20	1.0
Dew-point	Dew point (any liquid phase)	sum less than	°C (@ 20 bar)	-10	-10	-10
Solids	Full removal cut-off diameter	Less than	micron	1	1	1

Table 6.6 CO_2 specification comparison to other outstanding projects.

Northern Lights ([3]) and Aramis projects require CO_2 delivery for CCS Hub type of projects, which adds the complexity of having mixtures of different CO_2 streams. Both are also offshore storage project with the need of extra integrity assurance measurements for subsea facilities. Therefore, some of the specifications must be conservative when compared to a point-to-point CCS project and standard thresholds.

Nevertheless, Ebro composition could fit for most of the main parameters in Aramis project for pipeline transportation: CO_2, inerts, volatiles and dew point, critical feature for preventing risks of corrosion effect on pipelines and wells.

In Northern Light, as only shipping transport is available, delivery specification must be much more restrictive. However, as stated together with specification document, exceptions may be evaluated if necessary, in cooperation with the customer.

6.4 Upper Silesia Basin (Poland)

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

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

Table 6.7 Minimum CO2 content by capture technology

[3] https://norlights.com/how-to-store-co2-with-northern-lights/

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

Table 6.8 Maximum allowable impurities

Physical parameters of CO_2 (supercritical state) are:

- **Pressure**: minimum 8 MPa
- **Temperature**: between –20°C and +30°C

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

6.5 Macedonia Basin (Greece)

The CO_2 captured at Ptolemaida V plant is expected to be of high purity, particularly stable for geological storage as well as for potential industrial utilisation. The capture process is supposed to use amine-based post-combustion capture, which typically achieves a purity level of >95-99% of CO_2 stream (Koukouzas et al., 2021). This purity level is fundamental for the environmental safety and the efficiency of CO_2 injection into geological formations.

The flue gas composition of the existing power plants in West Macedonia, contains several trace impurities, which must be removed or treated appropriately during the CO_2 capture process. Table 6.9 mentions the type of impurities noted in flue gas in Ptolemaida, Agios Dimitrios, Kardia, and Meliti facilities (Koukouzas et al., 2021):

Metals	Particulate Matter	Gases
Arsenic (As)	PM_{10}	Nitrogen Oxides (NO_x/NO_2)
Cadmium (Cd)		Sulphur Oxides (SO_x/SO_2)
Chromium (Cr)		Carbon Monoxide (CO)
Mercury (Hg)		
Nickel (Ni)		
Lead (Pb)		

Table 6.9 Types of flue gas's impurities in West Macedonia lignite plants

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The CO_2 concentration in flue gases at lignite plants in West Macedonia, ranges between 10-14% by volume, depending on combustion conditions. It has been reported that prior to capture processes the temperature of flue gases are between 65-150 °C, varying by unit and operation mode. These parameters are essential for designing the capture unit, especially for amine-based systems, which require temperature conditioning to optimise solvent performance and ensure CO_2 condensation. Regarding the CO_2 stream capture from Ptolemaida V, it must comply with compositional standards suitable for injection into deep saline aquifers in the Mesohellenic Basin, specifically in the Pentalofos and Eptachori formations. The stream must be treated to meet generally accepted standards for non-corrosiveness and geochemical compatibility. These standards align with international CCS guidelines (e.g. ISO 27916:2019) and suggest that the detected H_2S must be below 100ppmv, the O_2 < 4% and H_2O (water vapor) should be minimized to avoid corrosion and hydrate formation (Koukouzas et al., 2021, Carneiro, J.F. and Mesquita, P.; 2020).

The high-purity CO_2 stream captured from Ptolemaida V is designed to follow the European standards for geological storage. Pre-treatment processes should manage typical flue gas contaminants ensuring the safe long-term storage in the Mesohellenic Basin. While the exact specifications depend on site-specific injection conditions and storage formation characteristics, they are expected to follow best practices established by ISO and EU CCS frameworks.

7. Transport

7.1 Paris Basin (France)

For the Paris Basin case, two scenarios are considered:

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

Based upon the well design proposed in section 8.1, the wellhead conditions are summarized in Table 7.1:

	$P_{wellhead}$ (kPa)	$T_{wellhead}$ (°C)
main scenario	96500	39
alternate scenario	12500	56

Table 7.1 Summary of the wellhead conditions for the scenarios considered for the French case

7.1.1 Main scenario

This scenario considers a J-shape well with a pipeline transport. The source of CO_2 is located about 3 km from the wellhead. The process flow diagram is shown in Figure 7.

7.1.1.1 General description

The CO_2 from the source must be compressed to reach the required injection pressure. The CO_2 passes first through filter separators to retain any droplet or particle that could be transported by the fluid and could damage the compressors. Then it must be compressed with 5 stages of compression. At the discharge of each stage, an intercooler is installed to cool the CO_2 at 50°C with ambient air. An optional separator is considered too at each discharge of compression. A final cooler will be required during summer (when the ambient temperature is higher than 30°C) to inject the CO_2 into the well at the required temperature. The pipeline between the installations and the wellhead has an estimated

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diameter of 6''. This diameter is chosen by applying velocity design criteria on the detail of the routing of the pipeline. Safety valves will be installed in different areas to isolate the installation in case of emergency.

7.1.1.2 Description of the main equipment

Filter separator (V1)

Two filter separators have to be installed in parallel. They will be designed with the following data:

- Configuration: horizontal with cartridges
- Normal flowrate per filter: 17 123 kg/h
- Extreme flowrate per filter: 34 247 kg/h
- Operating pressure: 101 kPa
- Operating temperature: 20°C
- Efficiency: liquid: 99% mass (5 µm cut-off diameter). Solid: 99.9% solid particles > 5 µm

Optional separators (V2/3/4/5)

Optional separators are considered downstream each cooler. The requirement for this equipment has to be confirmed in a later stage of the study with the vendor of compressor. Indeed, if the compressors are lubricated, these separators could be required to "de-oil" the compressed CO_2.

Compression unit (C1/2/3/4/5)

The compression unit is composed of 5 stages, with the following design data (Table 7.2):

Tag	C1	C2	C3	C4	C5
Technology	Centrifugal	Centrifugal	Centrifugal	Centrifugal	Centrifugal
Flowrate (kg/h)	34 247	34 247	34 247	34 247	34 247
Suction pressure (kPa)	101	254	712	2 075	6 023
Discharge pressure (kPa)	304	762	2 125	6 073	9 940
Electrical power (kW)	873	955	931	859	301

Table 7.2 Characteristics of the compression stages for the main scenario of the French case

The total electrical power is 3 919 kW.

Centrifugal compressors are foreseen. It is a type of dynamic compressor used to increase the pressure of a fluid by converting its kinetic energy into potential energy.

Air cooled heat exchangers (E1/2/3/4/5)

At the discharge of each stage of compression an air-cooled heat exchanger will be installed to cool the compressed CO_2 to 50°C.

Air cooled heat exchangers transfer heat from compressed CO_2 to ambient air. The CO_2 is contained within heat conducting tubes. Atmospheric air, which serves as the coolant, is caused to flow perpendicularly across the tubes in order to remove heat. Air stream is created by fans mounted on the unit.

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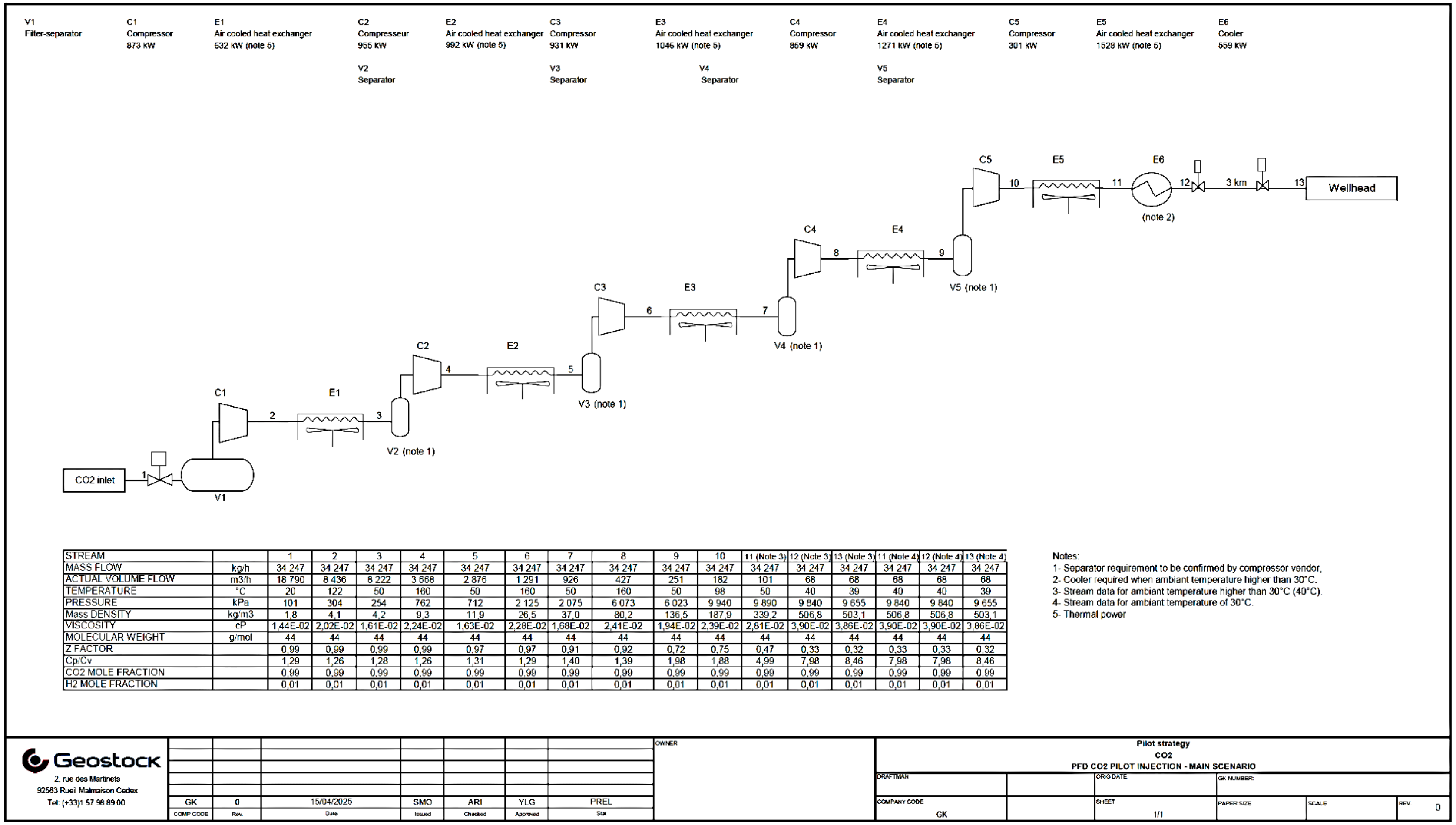

STREAM		1	2	3	4	5	6	7	8	9	10	11 (Note 3)	12 (Note 3)	13 (Note 3)	11 (Note 4)	12 (Note 4)	13 (Note 4)
MASS FLOW	kg/h	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247
ACTUAL VOLUME FLOW	m3/h	18 790	8 436	8 222	3 668	2 876	1 291	926	427	251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

Figure 7 Process Flow Diagram for the main scenario

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These exchangers will be designed with the following criteria (Table 7.3):

Tag	E1	E2	E3	E4	E5
Flowrate (kg/h)	34 247	34 247	34 247	34 247	34 247
Operating pressure (kPa)	304	762	2125	6 073	9 890
Upstream temperature (°C)	122	159,6	160	160	98
Downstream temperature (°C)	50	50	50	50	39,7
Thermal power (kW)	632	992	1 046	1 271	1 528

Table 7.3 Characteristics of the heat exchangers for the main scenario of the French case

Cooler (E6)

An additional cooler is required, when the ambient temperature is higher than 30°C. Indeed, for an ambient temperature higher than 30°C, the air-cooled heat exchanger E5 cannot cool the CO_2 to the required 39.7°C.

A loop with compressed/relieved CO_2 could be foreseen for the cooling media flowing through the exchanger. This solution needs to be studied at a later stage.

Tag	E6
Flowrate of main stream (kg/h)	34 247
Operating pressure of main stream (kPa)	9 890
Upstream temperature of main stream (°C)	50
Downstream temperature of main stream (°C)	39,7
Thermal power (kW)	559,5

Table 7.4 Characteristics of the heat exchanger required for summer season temperature for the main scenario of the French case

7.1.2 Alternate scenario

This scenario considers a long deviated well and no pipeline transport as the wellhead is located within the emission plant premises. The process flow diagram of this scenario is shown in Figure 8.

7.1.2.1 General description

The CO_2 from the source must be compressed. The CO_2 passes first through filter separators to retain any droplet or particle that could be transported by the fluid and could damage the compressors. Then it must be compressed with 5 stages of compression. At the discharge of each stage, an intercooler is installed to cool the CO_2 to 50°C with ambient air. An optional separator is considered too at each discharge of compression.

Safety valves will be installed in different areas to isolate the installation in case of emergency.

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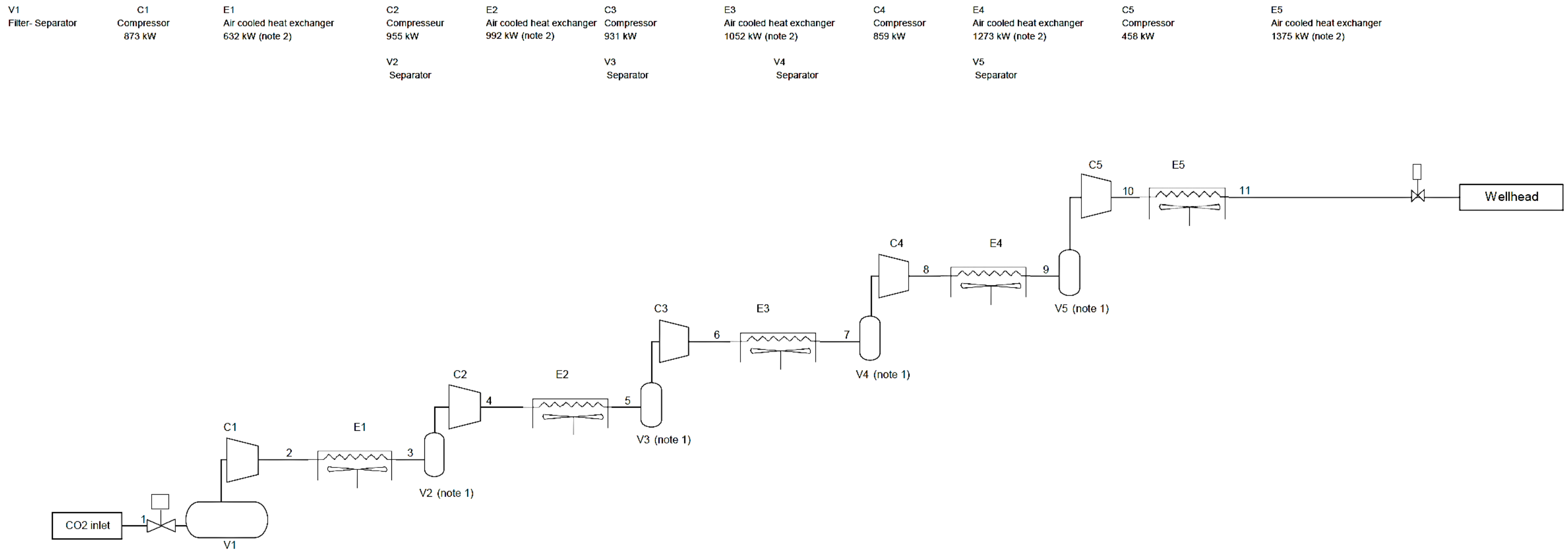

STREAM		1	2	3	4	5	6	7	8	9	10	11
MASS FLOW	kg/h	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247	34 247
ACTUAL VOLUME FLOW	m3/h	18 790	8 436	8 222	3 668	2 876	1 291	926	427	251	158	75
TEMPERATURE	°C	20	122	50	160	50	160	50	160	50	122	56
PRESSURE	kPa	101	304	254	762	712	2 125	2 075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

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

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Figure 8 Process Flow Diagram for the alternate scenario

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7.1.2.2 Description of the main equipment

Filter separator (V1)

Two filter separators have to be installed in parallel. They will be designed with the following data:

- Configuration: horizontal with cartridges
- Normal flowrate per filter: 17 123 kg/h
- Extreme flowrate per filter: 34 247 kg/h
- Operating pressure: 101 kPa (1 bara)
- Operating temperature: 20°C
- Efficiency: for liquid: 99% mass (5 µm cut-off diameter)
  solid: 99.9% solid particles > 5 µm

Optional separators (V2/3/4/5)

Optional filters separators are considered downstream each cooler. The requirement of the equipment must be confirmed in a later stage of the study with the vendor of compressor. Indeed, if the compressors are lubricated, these separators could be required to "de-oil" the compressed CO_2.

Compression unit (C1/2/3/4/5)

The compression unit is composed of 5 stages, with the following design data (Table 7.5):

Table 7.5 Characteristics of the compression stages for the alternate scenario of the French case

Tag	C1	C2	C3	C4	C5
Technology	Centrifugal	Centrifugal	Centrifugal	Centrifugal	Centrifugal
Flowrate (kg/h)	34 247	34 247	34 247	34 247	34 247
Suction pressure (kPa)	101	254	712	2 075	6 023
Discharge pressure (kPa)	304	762	2 125	6 073	12 550
Electrical power (kW)	873	955	931	859	458

The total electrical power is 4 076 kW.

Centrifugal compressors are foreseen. It is a type of dynamic compressor used to increase the pressure of a fluid by converting its kinetic energy into potential energy.

It is recommended to split at least the flow in two compression units installed in parallel to guarantee an acceptable reliability.

Air cooled heat exchangers (E1/2/3/4/5)

At the discharge of each stage of compression an air-cooled heat exchanger will be installed to cool the compressed CO_2 to 50°C. Air cooled heat exchangers transfer heat from compressed CO_2 to ambient air. The CO_2 is contained within heat conducting tubes. Atmospheric air, which serves as the coolant, is caused to flow perpendicularly across the tubes to remove heat. Air stream is created by fans mounted on the unit.

These heat exchangers will be designed with the following criteria (Table 7.6):

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Table 7.6 Characteristics of the heat exchangers for the alternate scenario of the French case

Tag	E1	E2	E3	E4	E5
Flowrate (kg/h)	34 247	34 247	34 247	34 247	34 247
Operating pressure (kPa)	304	762	2 125	6 073	12 550
Upstream temperature (°C)	122	159,6	160	160	121,5
Downstream temperature (°C)	50	50	50	50	56
Thermal power (kW)	632	992	1 046	1 271	1 375

7.1.3 Other equipment

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

Consider implementing advanced leak detection technologies, such as infrared cameras and gas sensors, which can help identify and address CO_2 leaks promptly.

The site will be equipped too with:

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

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

7.2 Lusitanian Basin (Portugal)

As referred to in previous reports, the transport methods during the Pilot phase are railway for onshore transport and shipping for offshore transport, with the ship being able to connect to the wellhead and proceed directly to injection. During the commercial phase transport is entirely by pipeline[4].

Although the economic viability is not relevant for the pilot phase, as it aims to prove the technical conditions in the reservoir and seal, the cost structure was estimated for both phases using the STRATEGY CCUS tool and the results of the CTS project that addresses specifically the transport component. The concept scenario for the Lusitanian basin CCS project was described in D4.3 and D4.9 deliverables of PilotSTRATEGY (Canteli, 2025a and b), but for clarity and since different transport strategies are considered for each phase, it is described in this section. The baseline scenario for the

[4] Truck transportation is not as primary option in this project or in previous projects, such as STRATEGY CCUS, but its feasibility is not completely discarded given the new estimates for the CO_2 volume that can be captured at BA GLASS factory. These are much lower than anticipated, and for which truck transport may provide a viable alternative to railway.

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Lusitanian Basin CCS project has been developed from earlier stages and framing sessions, and it includes two injection phases:

- **Phase I: Pilot-Scale Injection**
  - **CO_2 Sources**: section4.2, describes the possible sources for the pilot phase. According to the STRATEGY CCUS and CTS project, the CO_2 for the pilot phase is expected to be sourced from CIMPOR cement plant at Souselas, up to a maximum of 60 kt/year. The BA GLASS factory at Marinha Grande may also provide small amounts of CO_2. The NAVIGATOR pulp & paper facility near Figueira da Foz port may also be considered in this phase, since this company has announced plans for capturing CO_2 within the framework of a e-fuels production project and may move faster into CO_2 capture than CIMPOR.
  - **Volume and Duration**: STRATEGY CCUS project has projected that pilot capture facilities in Souselas cement plant and BA Glass factory at Marinha Grande would supply 90 kt/yr for this phase, leading to a total injection of 270 kt in 3 years. However, forecasts made in the CTS project point to residual volumes at the BA Glass factory, with the main source for this stage being the Souselas CIMPOR cement plant, that is 90 kt/yr in three years, or 180 kt in total. Depending on the source and available amount of CO_2 (see section 4.2), the volume of CO_2 to be injected during the pilot, particularly if sourced from NAVIGATOR, may be chosen to remain below 100 kt for the total duration of the pilot phase, to ensure the project qualifies as a research project under the Portuguese CCS law (DL 60/2012), in which no storage permit is required. If the volume of CO_2 available for 3 years of pilot stage exceeds 100 kt, a procedure for obtaining a storage permit will be launched during the first year of pilot injection.
  - **Transport**: CO_2 transported from the identified sources will be via railway transport to the Figueira da Foz port and then by ship with direct injection capacity to the injection site.
- **Phase II: Commercial-Scale Injection**
  - **Volume and Duration**: Up to 0.5 Mt/year over a 30-year timespan for the well drilled for the pilot stage. The STRATEGY CCUS scenario included the need to inject up to 4.7 Mt/yr by 2045, which would require multiple wells and, likely, the definition of other geological structures in the same reservoir.
  - **CO_2 Sources**: For the commercial phase, apart from the scale up of the capture at CIMPOR Souselas plant, CO_2 volumes will be scaled up to include industrial emitters and possibly new sources according to the scenarios developed in the STRATEGY CCUS and CTS projects. These included sourcing the CO_2 from at least five cement factory, one lime factory and three pulp & paper factories. However, for consistency, the cost structure considered in the PilotSTRATEGY commercial phase concerns only the same sources as the pilot phase.
  - **Transport**: The commercial phase transport is expected to be performed exclusively by pipeline both onshore and offshore. For emitters further away and with port access, such as the Sines and Setúbal port, ship transport and direct injection may also be considered, depending on the economic considerations. That analysis is not within the scope of PilotSTRATEGY and will be carried out in the CTS project.

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The injection strategy involves injecting CO_2 under a liquid or supercritical phase to maintain optimal pressure gradients and control the CO_2 plume. The main injection well will undergo an injectivity test to test reservoir properties and ensure efficient injection.

CO_2 transport options considered at this project stage result from the optimization from the original framing sessions and are here described. This optimization results from thorough analysis of both offshore and onshore pipeline solutions, weighing the feasibility, technical requirements, and economic implications of each option. Transportation can be summarized into two different options:

- **1 – Pilot Phase**: baseline scenario with railway from the local emitters to the Figueira da Foz hub (onshore) and then shipping (offshore) to the injection site
- **2 – Commercial Phase**: baseline scenario, with pipeline transport from the local emitters to the Figueira da Foz terminal (onshore), followed by offshore pipeline from the port to the injection site

The pilot phase and the commercial phase were evaluated for capital expenditure (CAPEX) and operating expenditure (OPEX), although the economic viability is not relevant for the pilot phase, as it aims to prove the technical conditions in the reservoir and seal.

7.2.1 Transport Conditions

The rationale for estimating the properties of CO_2 at various phases of its capture, transport, and storage is based on maintaining its optimal state for efficiency and safety. During the capture phase, CO_2 is typically in a gaseous state at low pressure and moderate temperature, suitable for initial separation from industrial processes. For railway transport, CO_2 is then converted to a medium pressure and low temperature (dense phase) to ensure stability and compactness for efficient tank transportation. When shipping CO_2, in the pilot phase, currently available options suggest it should be maintained in a dense phase at medium pressure, facilitating large-scale transport. Nevertheless, CO_2 should pass through an injection pump before being injected into the reservoir.

Phase		Pressure	Temperature	State of CO_2
Capture*		1 – 2 bar	40 – 60°C	Gas
Pilot-scale phase transport	Railway	6-15 bar	-50°C to -20 °C	Liquid Phase
	Onshore pipeline	80 up to 180 bar	Ambient temperature	Dense Phase
	Shipping	6-15 bar	-50°C to -20 °C	Dense Phase
Commercial scale transport	Pipeline (onshore and offshore)	80 to 120 bar	Ambient temperature	Dense / Liquid
Injection (ca. 1200 m depth)	Wellhead conditions	> 80 bar	Ambient temperature	Liquid
	Bottomhole conditions	180 – 230 bar	24 – 27°C	Dense/Liquid
	Reservoir conditions	165 – 200 bar+	40 – 50°C	Supercritical

*Table 7.7 Pressure and Temperature properties considered for each transport phase (Pilot and Commercial phases). Temperature and Pressure properties at the capture phase would be compressed into a medium pressure dense phase before onshore transport to the port. (*Although Capture is not part of the scope of the project, its parameters influence the facility considerations and need to be considered.)*

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For offshore pipeline transport, during the commercial phase, CO_2 received by the local sources should be kept in a dense or supercritical state at high pressure and moderate temperature, before being injected. CO_2 injected into the reservoir at significant depth would be at high pressure and in a dense/supercritical state to optimize storage capacity while assuring reservoir stability.

In the pilot stage, CO_2 is transported via train wagons in storage tanks which transport CO_2 at pressures ranging from 6.5 bar to 15 bar and temperatures from -50°C to -20°C. Therefore, the captured CO_2 should be conditioned to fulfil the delivery requirement for selected mode. Captured CO_2 from the emitter can be delivered at 1 bar 25°C. To transport in storage tanks, CO_2 must go through a series of compression and refrigeration processes (to achieve high-density stage), see Figure 9. The refrigeration process will cool the gas to saturated liquid point using ammonia compression refrigeration cycle.

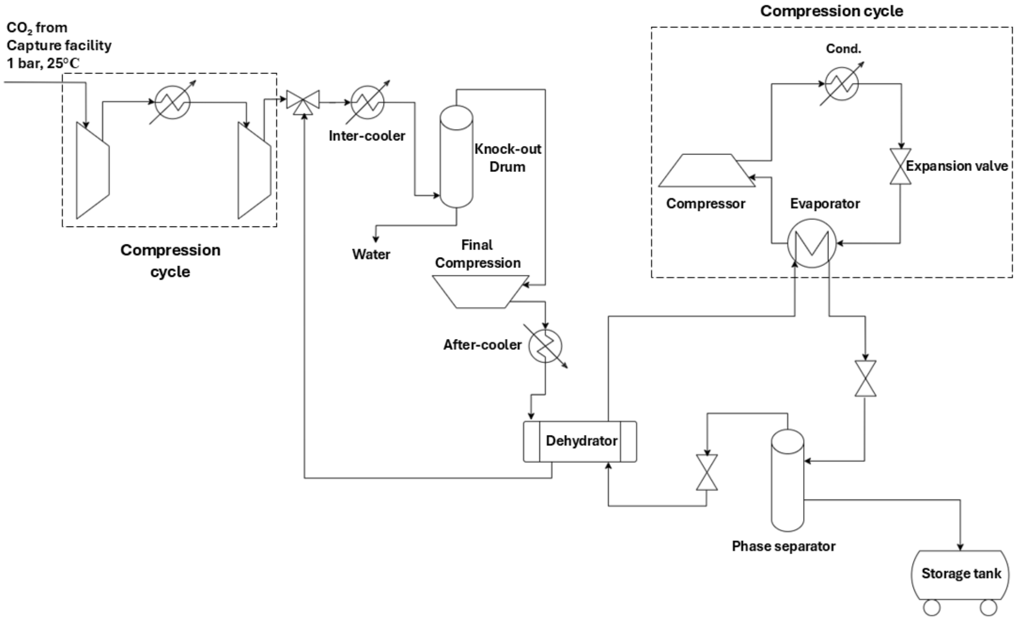

Figure 9 CO_2 compression and refrigeration cycle to store CO_2 in tanks.

Captured CO_2 is compressed in multiple stages with intercooling and knock-out drums to increase the efficiency and reduce any condensates. This compressed CO_2 is again cooled in after-cooler before going into dehydrator where all the condensates are eliminated. Here, cooling of recirculated gas is used to cool down the compressed CO_2, this is done to reduce the risk of icing. The compressed CO_2, say to 6.5 bar, is refrigerated in ammonia-based refrigeration cycle to attain -50°C to -20°C requirement. At last, before storing, the saturated liquid CO_2 enters a "Phase Separator" where any gases are extracted and recirculated back into the system. Figure 10 shows the T-S diagram of the complete CO_2 cycle. At the end of the process, CO_2 is stored at the required pressure and temperature in storage tanks, ready to be transported.

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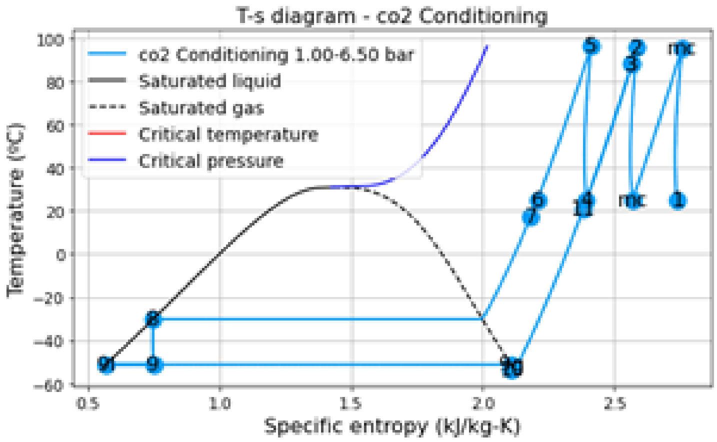

Figure 10. T-s diagram of the CO2 conditioning process from capture to storage tank with 3 compressors. Example for cooling transport at 6.5 bar and -50℃

Using the T-s and P-h diagram, the work done by compressor can be calculated using Compressor Work-done equation under isentropic efficiency. The size of compressor depends on the isentropic efficiency, compressor efficiency, compression stages and compressor efficiency. For the compression of 60kt annual CO_2 under stated conditions, a 3-stage compressor with 276 kW is required. Similarly, using the curves, cooling required to bring down CO_2 at -50°C is shown. A cooling system with the capacity to extract 144 kW from the flowing gas is required.

Equipment name	Specification	Value
CO_2 Compressor	3-stage with inter cooling and water trap	**276 kW**
CO_2 Refrigeration	Ammonia based refrigeration system	**144 kW** (required cooling)

Table 7.8 Equipment specifications.

- **Shipping Design Conditions (Pilot Phase)**

Several challenges are envisaged during shipping transport for about 90 kt/year CO_2 injection, for 3 years. These challenges include:

  - **Pressure Management**: The recommended shipping pressure of 70 bar exceeds the current CCS industry practice of 40 bar. This higher pressure (HP) may pose operational challenges and increase shipping and storage costs, and that is the reason why medium pressure (MP) (15 bar) should apply in this case
  - **Vessel Supply**: The supply chain for such specialized vessels is limited, which could lead to delays, and that is why it would be required MP shipping (solutions found in the market estimate about 15 bar at low temperature)
  - **CO_2 Purity**: Current CCS industry practices assume very high purity CO_2 (>99.7 mol%). Ensuring this level of purity may require additional processing and quality control measures

- **Pipeline Design Conditions (Commercial Phase)**

After the Pilot phase, the design conditions for CO_2 transport should be estimated, considering the fluid properties, to ensure dense phase flow during injection. The average inlet flowrate for CO_2 injection is calculated based on the annual storage rate and the system uptime. The industry standard

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recommends a system uptime of 95%, which accounts for maintenance and unexpected shutdowns. The mass flowrate can be estimated using the formula:

$$Mass\ Flowrate = \frac{\text{Storage Rate}}{\text{System Uptime}}$$

Given the Annual Storage Rate of *ca*. 0,5 Mt (i.e. 5×10^{9} kg), a System Uptime of 95%, the Mass Flowrate can be retrieved as 16,8 kg/s.

The pressure conditions for the offshore pipeline are designed to ensure that pressure at the wellhead is enough to guarantee that bottomhole pressure is above 180 bars required for injection in the reservoir and ensure safe margins of operation. Ambient temperature can be adopted for the full length of the pipeline, since the temperature conditions in the seabed in the Atlantic coast of Portugal, at water columns shallower than 100 m are above 10°C, enough to ensure dense phase, but high enough to prevent hydrate formation. These conditions ensure that CO_2 remains in a dense phase, optimizing transport efficiency and safety.

7.2.1.1 Railway

Transport via railway was the option previously considered as the best option to redirect CO_2 from the point sources of CIMPOR and BA Glass, located in Souselas and Marinha Grande, respectively (see Deliverable 4.3 “Final concept description and preliminary consideration by regions” (Canteli, 2025b)), and that remains the main option (Table 7.9), although the possibility of capturing from the glass factory seems remote, at this stage.

Railway transport of CO_2 is considered a cost-effective option for medium-range distances, particularly relevant for industries like cement, pulp & paper and glass located in central and northern Portugal. Applying the STRATEGY CCUS tool that evaluates the full-chain costs not only for individual sources, but also for a cluster-and-hub approach, taking into account several geographic features and technological options, we estimated the costs only for transport from the CIMPOR Souselas cement plant.

	Distance (km)	Flow Rate (kt/year)	CAPEX (€M)	OPEX/Year (€M)	Total 3-Year Cost (€M)
CIMPOR (Souselas)	65	30	2,2	0,035	**2,3**

Table 7.9 Summary of Class V estimated CAPEX and OPEX for annual and 3-year (Pilot) lifetime railway transport, from the Souselas source to the Figueira da Foz port.

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7.2.2 Pilot Phase: Shipping with direct injection

Shipping transport offers several advantages for the pilot phase of the Lusitanian Basin project. One of the primary benefits is flexibility. Shipping allows flexible transport options, including direct injection from the ship, which can avoid the deployment of offshore pipelines or platforms at an early stage, where the injection concept and reservoir performance need validation. This flexibility is particularly advantageous for pilot projects with variable CO_2 volumes, as shipping can be scaled up or down based on the volume of CO_2 to be transported.

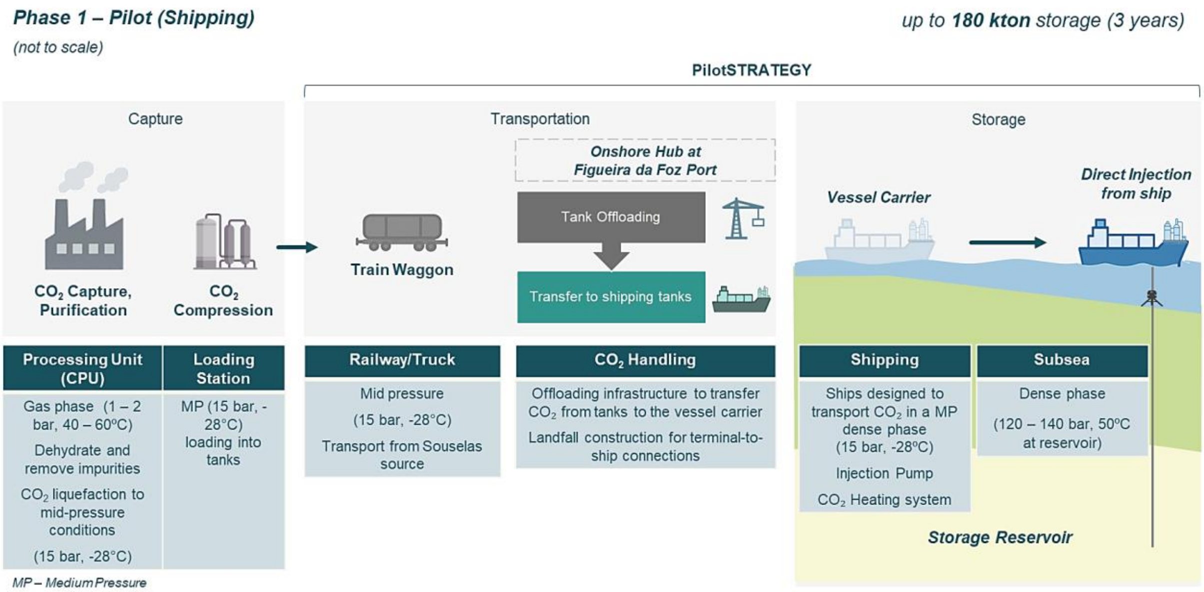

Figure 11 Conceptual workflow of the Reception and Injection facilities for the Pilot Phase (transport pressure and temperature conditions are indicative)

Another significant advantage of shipping is the lower initial investment required. The initial CAPEX for shipping infrastructure includes unloading at the intermediate hub, which would require landfill construction at the terminal), as well as the cost of CO_2 carriers designed to transport and directly inject CO_2 in a dense phase. Notice that the hub is merely for transfer of tanks from trains to the ship, without reconditioning being required. Based on typical industry costs, for a target capacity of 180 kt over the course of 3 years, the CAPEX includes costs for acquiring a small-scale (or retrofit) CO_2 carrier with two storage tanks (800-1000 m^3), injection pumps and offloading hoses (29 M€ - still under validation, annualized value for 3 years, considering a total CAPEX of ~67 M€ and a ship lifespan of 25 years), and an onshore CO_2 hub (port terminal) for transfer to ship and the initial liquefaction at the CO_2 source (6 M€). The OPEX includes costs for CO_2 carriers (€7 million/year), for liquefaction and loading / unloading facilities (1.2 M€/yr). Costs of transport by train are also here included, with CAPEX 1.5 M€ annualized value for 3 years, considering a total CAPEX of ~12 M€ and a locomotive and wagon lifespan of 25 years, and an annual OPEX of 0.5 M€. These cost components amount to a total cost for the transport component of 87 M€ for the three-year pilot (Table 7.10).

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	Component	CAPEX	OPEX/Year	Total OPEX over 3 years	Total 3-Year Cost
Railway	CIMPOR (Souselas)	1,5	0,50	1,5	3,0
Figueira da Foz Hub	Onshore CO_2 Hub (Port Terminal)	6	1,2	3,6	9,6
Shipping	CO_2 Carrier (including a used, small-scale skip, two storage tanks 800-1000 m^3)	9	7	21	30,0
	Injection pumps and offloading hose for connection to well	20			20,0
	Injection Well + Subsea Manifold	30	8	24	54,0
	Control Systems, Power Supply	5			5,0
TOTAL	**Pilot Phase**	**72**	**17**	**50**	**122**

Table 7.10 Summary of Class V estimated CAPEX and OPEX cost ranges for the Pilot Phase based on the STRATEGY CCUS project for the transport component, IEAGHG (2020), DNV-RP-J203 for other components

**Annualized value for 3 years, considering a total CAPEX of ~12 €M and a locomotive and wagons lifespan of 25 years.*
***Annualized value for 3 years, considering a total CAPEX of ~48 €M and a ship lifespan of 25 years.*

Shipping schedules can be affected by weather conditions, potentially causing delays in CO_2 transport. Some challenges include significant cost uncertainties across the entire transport chain due to the lack of mature CCS projects using this system. This variability can impact the overall project budget. Furthermore, delays in the supply chain, including the availability of specialized vessels and equipment, can lead to longer delivery times than currently estimated. To act as a buffer in case of shutdowns at the carbon sources or delays in ship arrivals at the port, one solution to minimize the impact of this operation at the shallow-water (6,5 – 8,5 m water depth) port is to have a two-ship solution, in which there would be one smaller ship collecting CO_2 (capacity for one injection cycle) at harbor, while the injection vessel is at the field, closer to the storage site. This would need to be aligned with the available CO_2 at the receiving terminal and the reservoir injection strategy.

Additional considerations for this scenario include the need for onboard CO_2 compression to reach reservoir injection pressures, which typically range from 90 to 150 bar depending on geological conditions. The relatively shallow water depth of 85 meters simplifies offshore infrastructure deployment but still requires compliance with marine safety and environmental standards. The project’s scale favors modular or repurposed systems, offering potential for cost reduction through asset reuse or integration with future full-scale CCS developments. Despite the high per-tonne cost, this type of setup may be appropriate for this pilot phase, where proof-of-concept and regulatory development are primary objectives.

7.2.3 Commercial Phase: Pipeline Transport

Pipeline transport is more suitable for the commercial phase of the Lusitanian Basin project due to its higher capacity and operational efficiency. Pipelines can transport large volumes of CO_2 continuously, making them ideal for large-scale operations. Once installed, pipelines have lower OPEX compared to shipping, as they do not require fuel or crew. This results in significant cost savings over the long term.

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The initial CAPEX for pipeline infrastructure is significantly higher due to the costs of materials, construction, and regulatory compliance. In previous stages of this project, it was assumed an 8" pipeline, based on best practices and industry references.

The 23 km offshore pipeline from the Figueira da Foz port to the injection site implies challenges, but offshore pipeline transport of CO_2 is done currently at the Snohvit and Ravenna projects and will soon start at the Northern Lights and Porthos projects. Pipeline integrity needs careful material and coating selection to avoid CO_2 corrosion. Flow assurance should be considered to prevent blockages and phase changes due to pressure drops, temperature shifts, and hydrate formation. Environmental impact assessments and regulatory compliance are required for marine ecosystems, seabed preservation, and help managing local stakeholders. Operationally, installation, maintenance, and advanced monitoring systems are complex. Economically, construction, operation, and supply chain uncertainties can increase costs and extend delivery times.

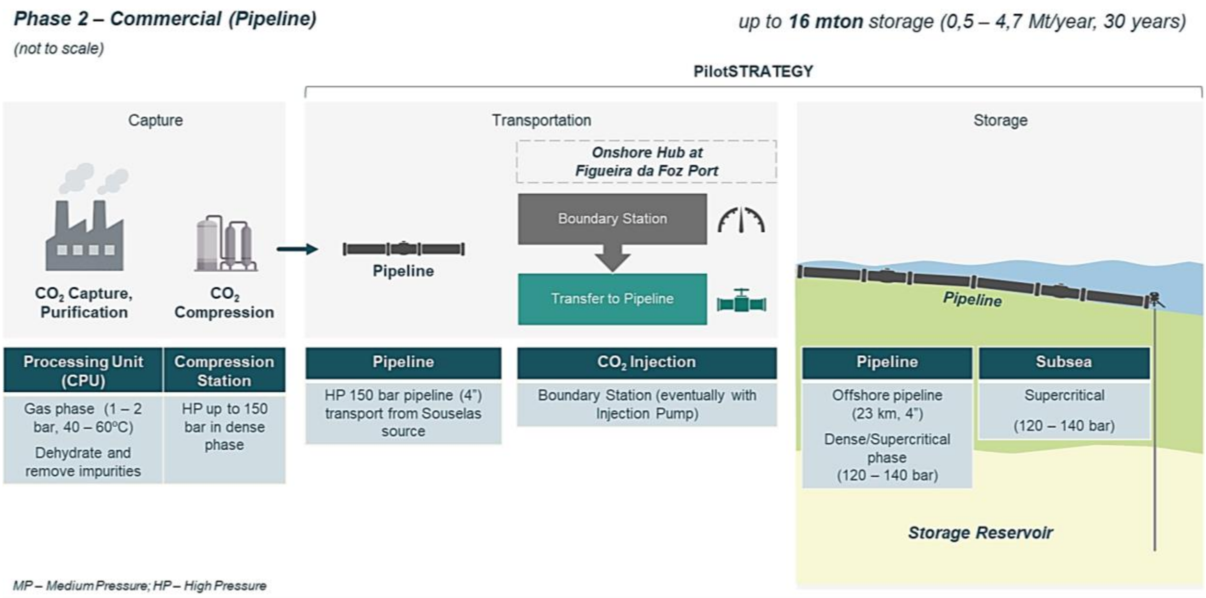

Figure 12 Alternative conceptual workflow of the Reception and Injection facilities for the Commercial Phase, with the connection by pipelines between the source and the onshore hub at the Figueira da Foz port (Transport pressure and temperatures are indicative)

We do not refer here to the costs of onshore pipeline construction during the commercial phase, as that needs to address the full scope of possible sources interested in storing the CO_2 at the site and not only three sources previously identified. The reader is referred to Deliverable 5.3 of STRATEGY CCUS (Coussy et al. 2022) for a thorough analysis of those costs.

The initial CAPEX for pipeline infrastructure is significantly higher due to the costs of materials, construction, and regulatory compliance. Based on the costs estimates made within the CTS project, the estimated CAPEX for a 23 km offshore pipeline is approximately 24 M€ (one-time cost). Notice that the pipeline is designed for a full transport capacity of 4.7 Mt/yr, as indicated in the STRATEGY CCUS project as the final amount of CO_2 being transported by 2045 (Table 7.11).

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	Component	CAPEX (M€)	OPEX/Year (M€)	Total OPEX over 30 years (M€)	Total 30-Year Cost (M€)
Onshore Pipeline	CIMPOR (Souselas)	27,7	1,5	40,5	68,2
Figueira da Foz Hub	Injection Pump	5	0,5	13,5	18,5
Offshore Pipeline	Offshore Pipeline	24	1,5	40,5	64,5
	Injection Well + Subsea Manifold		8	216	216
	Maintenance and Monitoring	5	1	27	32
TOTAL	***Commercial Phase***	***62***	***13***	***338***	***399***

Table 7.11 Summary of estimated CAPEX and OPEX facility costs for the Commercial Phase (pipeline options) based on STRATEGY CCUS

*Pipeline from Souselas cement factory to the hub connecting to the offshore pipeline

Despite the high initial investment, the lower OPEX makes pipelines a more economically viable option for large-scale CO_2 transport. Pipeline transport also provides a controlled and continuous injection rate, enhancing operational efficiency. However, obtaining permits and regulatory approvals for pipeline construction can be time-consuming and complex. Pipelines are also a fixed infrastructure, which limits flexibility and scalability compared to shipping.

7.3 Ebro Basin (Spain)

Transport concept for Ebro Basin project must be different depending on the CO_2 flow rate to be abated. For commercial scenario (0.5 Mtpa) pipeline transport is considered the optimum option. For pilot and low volume scenarios, only truck tanker transport is considered economically feasible.

7.3.1 CO_2 Compression

CO_2 compression is an essential preliminary step in the CCS value chain when pipelines are used for transport. Typically, as assumed in Ebro case for commercial scenario, the purified CO_2 produced by capture plants would be at or near ambient pressure (~1 bar). In most cases, this CO_2 is also saturated with water vapour.

When CO_2 is compressed to a pressure above the critical pressure of CO_2 (~74 bar for pure CO_2) its density increases significantly (Figure 13). At this point the CO_2 enters the “dense phase”. This higher density enables higher CO_2 tonnages to flow through pipelines. Additionally, this density is necessary when the CO_2 is delivered to the storage well.

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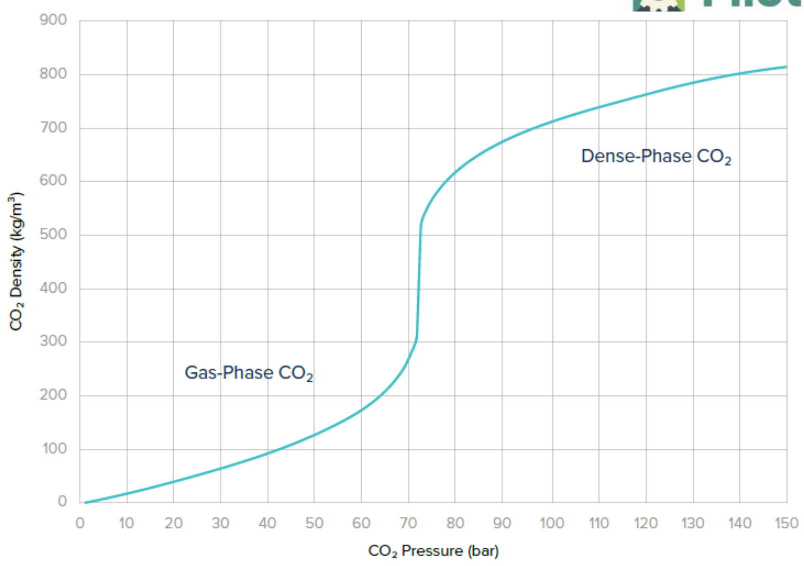

Figure 13 CO2 density at 30ºC as a function of pressure. Global CCS Institute

A typical compression arrangement considered appropriate for Ebro project commercial scenario concept is shown in next Figure 14. It consists of multiple compression stages, each followed by an aftercooler. Compression not only increases pressure, but also temperature. As compression energy is a function of gas volumetric flowrate, the coolers reduce the temperature, and therefore the volume, before moving on to the next stage of compression. The intent is to keep temperatures within reasonable limits and to keep energy consumption down.

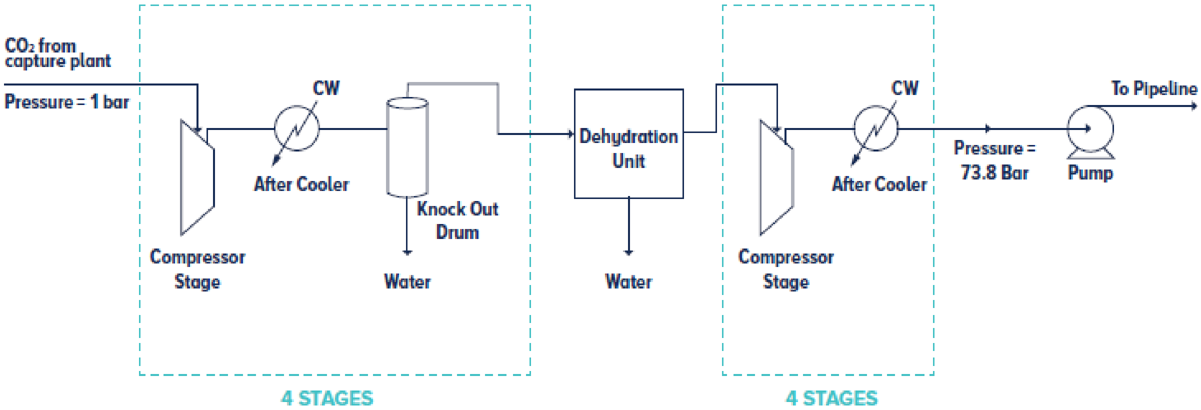

Figure 14 8-stage CO2 compression system with integrated dehydration

The compression system is also integrated with steps to remove water. Water must be removed to very low concentrations to prevent the formation of acids that can attack steel in pipelines and other downstream equipment. As CO_2 is compressed and cooled in the first few stages, liquid water will condense as the partial pressure of water exceeds its vapour pressure. This is removed in each stage under gravity in vertical vessels called knockout drums. After 3-4 stages of compression, little further liquid water will be produced. Further water removal requires a dehydration system (using a solid adsorbent or a liquid-based desiccant) to remove moisture to ppm levels.

For estimating the work consumption of the compression system necessary for transporting the CO_2 stream via pipeline it was assumed that a similar 8-stage compression unit would be necessary to reach the CO_2 dense-phase conditions (25ºC, 75 barg for Ebro stream compositions) for the

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commercial operation stage (0.5 Mtpa), McCollum & Odgen formulae were utilized for sizing the compression equipment. 8-stage compression system was selected as proper configuration as this is consistent with industry practices. Other similar schemes have been used in different equivalent projects worldwide.

In the following Table 7.12 and Table 7.13 can be found the expected pressures along the different compression stages, and the compressor work for each stage.

COMPRESSOR STAGE	PRESSURE INLET (BAR)	PRESSURE OUTLET (BAR)
1	1.00	1.71
2	1.71	2.93
3	2.93	5.02
4	5.02	8.59
5	8.59	14.71
6	14.71	25.18
7	25.18	43.11
8	43.11	73.80

Table 7.12 Compressor stages pressure

COMPRESSOR STAGE	POWER REQUIREMENT (kW)
1	699
2	696
3	692
4	684
5	669
6	644
7	599
8	503
TOTAL	**5,186**

Table 7.13 Compressor unit power requirement

Total power demand from compression process in Ebro Basin project would be close to **5.2 MW**.

7.3.2 Transport concept

7.3.2.1 Pipeline – Commercial scenario

The eighth compression stage boosts the CO_2 to its critical pressure (73.8 bar). At this point, CO_2 transitions into the "dense phase". Dense-phase CO_2 is essentially incompressible (like a liquid) and can be pumped like a liquid. This option is considered as the optimum concept for the commercial scenario in Ebro project (0.5 Mtpa till reaching the reservoir maximum capacity).

For sizing the pumping unit and the pipeline necessary to transport the dense phase CO_2 from emitter to injection site in Lopín, HYSYS 12.1 software was utilized. Aspen HYSYS v12.1 is a powerful process

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simulation software widely used in the energy industry for optimizing 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.

The pump outlet pressure depends on the pressure drop in the downstream pipeline, which varies with the pipeline length and diameter, relative heights above sea level between emitter and injection site and delivery conditions. As previously mentioned, for all the cases evaluated, the CO_2 is delivered in dense phase (Liquid phase) to the Injection plant at certain delivery conditions (for Ebro, always 30ºC and 85 barg). See HYSYS diagram in Figure 15.

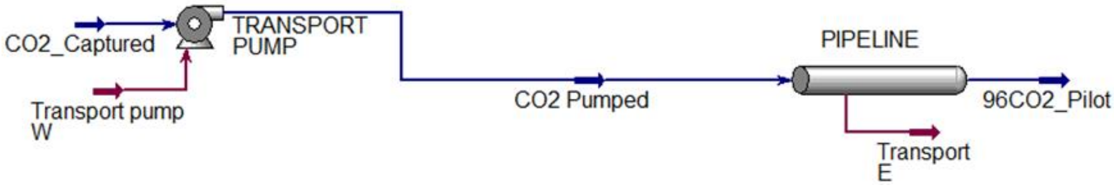

Figure 15 HYSYS scheme for pumping and transport from emitter to Lopín

Two different cases have been simulated depending on the possible distance from potential emitter to Lopin site to find the most favourable integrated configuration in terms of facilities size (pipeline and pumps) and energy consumption (for pumping). As Lopin area is located at a higher altitude above sea level than industrial area close to Zaragoza, both cases consider an overall positive slope (upwards) to reach injection site (Table 7.14).

Table 7.14 Transport scenarios description

	Distance from emitter to Lopin	Altitude difference
Best case	15 km	+70 m
Worst case	35 km	+120 m

The results are shown in the following Table 7.15 In bold are shown the optimum sizes selected.

Table 7.15 Pumping and pipeline sizing for different transport scenarios

Distance to emitter (km)	Pipeline nominal diameter (inches)	Pumping power required (kW)
Short (15 km; SAICA PAPER)	6”	300
Short (15 km; SAICA PAPER)	**8”**	**150**
Short (15 km; SAICA PAPER)	10”	120
Long (35 km; ESCATRON)	8”	240
Long (35 km; ESCATRON)	**10”**	**150**
Long (35 km; ESCATRON)	12”	140

Regarding the design of pipelines, the ISO-13623 standard "Petroleum and natural gas industries - Pipelines transportation systems" 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 31839. In all cases assessed, the transport pipeline would be manufactured in high resistant steel X52 with standard schedule:

- Short case: 8.2mm wall thickness
- Long case: 9.3 mm wall thickness

7.3.2.2 Truck – Low volume scenario and pilot stage

For the extreme low scenario (2 Mt injected with 1 well in 30 years) and pilot stage (30 kt/y during one year) the pipeline transport is considered not economically feasible as the volumes are too low to justify the necessary investment in a dedicated pipeline.

In its place, the supply of the necessary CO_2 volumes (approx. 195 tCO_2/day for low scenario and 85 t/day for the testing the pilot) will have to be done by truck from a nearby CO_2 supplier within the industrial area of Zaragoza (max. 40-50 km far). Considering the usual capacity of 30 m^3/truck, between 6 and 7 routes per day shall be completed to assure the daily volume. This could be achieved using a fleet of 2 tankers with full-time dedication.

7.3.3 Costs outline

Pipeline transport cost is directly related to the distance transported, the volume of CO_2 transported, and whether CO_2 is piped in the gas- or dense-phase. Pipeline costs are particularly sensitive to CO_2 volume, with most economies of scale being exploited above 1 Mtpa of CO_2. For CO_2 compression, costs are primarily driven by the volumes of CO_2 being handled and the price of electricity.

7.3.3.1 Compression

Compression capital cost depends directly on flow per train, number of trains, and the pressure ratio for the full compression system (1 to 73.8 bar). The formula used (McCollum & Odgen, 2006) is a regression of historical compressor prices.

For Ebro commercial scenario, only one compression train is envisaged, and the expenditure estimation would consider the following items:

Table 7.16 Compression process expenditures estimation for commercial scenario

CAPEX	M€
Pre-FID costs	3.11
Compressor supply	16.02
Assembly and commissioning	7.89
Engineering + Project Management	3.59
TOTAL CAPEX	**30.61**
OPEX	**M€/year**
Operation & Maintenance	1.2
Energy consumption*	2.55
Insurances & Others	0.36
TOTAL OPEX	**4.11**
ABEX	**3.59 M€**

*This work assumes a local electricity price of 0.075 EUR/kWh and a capacity factor of 90%.

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7.3.3.2 Pumping & Pipeline transport

As would be expected, pumping costs (capital and operational) are much less than compression costs, consuming less than 5% of total energy of the system from captured CO_2 delivery to subsurface injection.

For Ebro commercial scenario, pump and pipeline costs will depend directly on the source location (distance to Lopin and relative altitude), as other parameters (composition, pressure delivery at source…) are assumed to remain constant. The moderate size of the project (max. 0.5 Mtpa injected) won't allow to take advantage of economies of scale effects.

For estimating the preliminary costs, regressions on historical available in-house data for pumping and pipelines have been used, together with GCCSI report (Barlow et al., 2025) and McCollum & Ogden (2006) formulae. Results for both better and worse (close and far) scenarios are shown in the following Table 7.17 and Table 7.18

Table 7.17 Ebro commercial scenario, pump and pipeline, short distance scenario expenditures estimation.

Short distance scenario (15 km)	
CAPEX	M€
Pre-FID costs	1.22
Pumps supply	1.01
Pipeline supply	1.98
Assembly and commissioning	6.46
Engineering + Project Management	1.42
Land acquisition & Permitting	0.85
TOTAL CAPEX	**12.94**
OPEX	**k€/year**
Operation & Maintenance	178.9
Energy consumption*	125.78
Insurances & Others	141.81
TOTAL OPEX	**446.49**
ABEX	**M€**
Pumps decommissioning	0.15
Pipeline abandonment	1.19
Land remediation	0.60
TOTAL ABEX	**1.84**

*This work assumes a local electricity price of 0.075 EURkWh and a capacity factor of 90%.

Table 7.18 Ebro commercial scenario, pump and pipeline, long distance scenario expenditures estimation.

Long distance scenario (35 km)	
CAPEX	**M€**
Pre-FID costs	3.2
Pumps supply	1.01
Pipeline supply	5.77
Assembly and commissioning	17.82
Engineering + Project Management	3.66
Land acquisition & Permitting	2.35
TOTAL CAPEX	**33.88**
OPEX	**k€/year**
Operation & Maintenance	389.93

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Energy consumption*	125.66
Insurances & Others	285.50
TOTAL OPEX	**811.09**
ABEX	**M€**
Pumps decommissioning	0.15
Pipeline abandonment	3.47
Land remediation	1.39
TOTAL ABEX	**5.01**

*This work assumes a local electricity price of 0.075 eur/kWh and a capacity factor of 90%. (2024)

7.3.3.3 Tanker truck transport

CO_2 flow rate significantly impacts transport efficiency. Higher flow rates tend to reduce the unit cost of CO_2 transport, as more CO_2 can be shipped per trip, maximising storage and shipping capacity utilisation.

One or two tankers fleet doing 2-3 routes per day would be necessary to fulfil the required flowrate depending on the scenario (30 ktpa for pilot stage previous to commercial exploitation; or 70 ktpa till reaching a total volume of 2 Mt of CO_2 injected) and the distance from Lopin to the CO_2 source.

The cost of tanker transport in Spain currently varies between 1.3 and 1.5 €/tanker·km (Spanish Transport Ministry). This would imply an annual transport cost between 100 k€ and 350 k€/year depending on the scenarios described and the distance between CO_2 source and Lopin.

7.4 Upper Silesia Basin (Poland)

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

- Road transport by cryogenic tankers, intended for small quantities of CO2, mainly during the pilot phase.
- Pipeline transport, as the target solution for large-scale operations in the commercial phase.

Option I – Road Transport of CO2

Road transport involves cryogenic tankers capable of carrying 20–25 tonnes of liquefied CO2 per trip. CO_2 is transported in a liquid state at approximately –20°C and 17–25 bar.

Assumptions:

- Pilot phase transport volume: 30 000 tonnes of CO_2 per year
- Estimated number of truckloads per year: ~1 500
- Daily average: 4–6 tankers

Calculated costs:

- Unit transport cost by road: 0.23 EUR/km/t CO2
- For an 80 km route: 18.40 EUR per ton

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- Annual transport cost (30 000 t): approx. 552 000 EUR
- Total pilot phase cost over 3 years: approx. 1.66 million EUR

Road transport results in additional traffic, exhaust emissions, noise, and risks in urban or suburban areas. It is a flexible but less sustainable long-term solution.

Option II – Pipeline Transport of CO2

The CO_2 will be transported in a dense phase (supercritical or compressed gas) at approx. 12 MPa and 27°C. Various route lengths are considered: 30, 60, 80 or 120 km. The reference case is 80 km.

Exemplary pipeline parameters and assumed costs:

- Length: 30 / 60 / 80 / 120 km
- External diameter: 114–219 mm (depending on throughput)
- Operating pressure: approx. 12 MPa
- Material: carbon steel
- Average construction cost: 2.3 million EUR/km
- Total cost for 80 km: 184 million EUR
- Operating cost: 0.01 EUR/km/t CO_2 → 0.80 EUR/t CO_2

Assumed amount of carbon dioxide:

- Pilot phase: 30 000 t/year
- Commercial phase: 300 000 t/year

The pipeline system is designed to accommodate higher volumes in the future. Associated infrastructure includes:

- Compression stations at the inlet, and optionally midline depending on terrain
- Control and automation system (SCADA)
- Shut-off valves every 1–6 km, especially in urban or sensitive areas
- Anti-corrosion and leak prevention systems
- Real-time monitoring of pressure and flow using sensors and wave detection devices

For the pilot phase (30 000 t/year), road transport offers flexibility, simplicity, and lower upfront investment. For the commercial phase (300 000 t/year), pipeline transport is significantly more cost-effective, safer, and environmentally preferable.

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

Compliance with Legal and Technical Standards

The transport infrastructure must comply with:

- Directive 2009/31/EC (CCS Directive)
- Polish Geological and Mining Law (Journal of Laws 2011 No. 163 item 981)
- Regulation (EU) 601/2012 on monitoring and reporting of GHG emissions

Applicable technical standards include:

- ISO 27913:2016 (Carbon dioxide capture, transportation, and geological storage)
- API 5L and PN-EN 10020 for pipeline steel
- Additional safety documentation: risk assessment, emergency response plans, monitoring strategy

7.5 Macedonia Basin (Greece)

The Mesohellenic Basin (MHB) has the pontential to serve as a regional storage solution, supporting South-East Europe's net-zero goals through cross-border cooperation. The Greek scenarios focus on CO2 transport and storage in saline aquifers. Existing infrastructures at Agios Dimitrios and Ptolemaida can be used as CO2 hub, collecting emissions from various sources.

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 16):

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

- 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.

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Figure 16 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, like 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 8).

- 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 goal for handling continuous and large-scale CO_2 transport, given their ability to handle high volumes and provide a more permanent solution.

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8. Reception and injection facilities

8.1 Paris Basin (France)

The petrophysical properties and depths of the formations (Table 8.1) are the same as in previous report (Chassagne et al, 2024) but are complemented by thermal properties from literature (Dentzer et al, 2018). The temperature at the middle of the perforated interval is estimated at about 62°C for a mean pressure of about 20100 kPa. The maximum pressure for injection is estimated at 21200 kPa (Chassagne et al, 2024).

Table 8.1 Expected lithostratigraphic column at the bottom hole location for PSTY-01 – vertically from geological to surface (Ground level at 108m elevation from MSL)

		Top Depth (m TVDSS)	Top Depth (mTVD GL)	Lithological description	Reservoir / Caprock	Fluids
TERTIAIRE	**Oligocene**	-108	0	Shales, some limestones		
	Eocene			Mudstone, sands, clays		
CRETACE	**Senonian Turonien**	28,9	136,9	Chalks with some cherts		
	Cenomanian	602,3	710,3	Limestones		
	Shaly Albian (Argiles du Gault)	686,3	794,3	Claystones, sandy		
	Sandy Albian - Sables verts	729,3	837,3	Sands	Albian	Water
	Albo aptian	773,7	881,7	Sands and clays		
	Barremian	862,3	970,3	Claystones, sandy, silt, sandstones		
	Neocomian			Claystones, sandy, sandstones and sands		
JURASSIQUE	**Purbeckian**	1025,7	1133,7	Limestones mudstone. Dolomites, anhydrites		
	Portlandian	1060,7	1168,7	Limestones mudstones, some shales		
	Kimmeridgian	1181,8	1289,8	Shales, silty		
	Upper Oxfordian - Lusitanian	1346,8	1454,8	Limestones mudstone, silty		
	Lower Oxfordian	1617,0	1725,0	Shales, silt, pyrite, some limestones.	Caprock 2	
DOGGER	**Upper Callovian CA28**	1724,2	1832,2	Shales and clays chalky	Caprock 1	
	Lower Callovian - Dalle nacrée - Comblanchien = CA26	1734,1	1842,1	Limestone, slight clay		Water
	Bathonian - Oolithe Blanche = SB_Comb	1765,2	1873,2	Limestones	Oolithe blanche	Water
	Bathonian - Bt10	1865,7	1973,7	Limestones		Water
	Bajocian = BJ1	1925,9	2033,9	Shales, silt. Limestones		
LIAS	**Aalenian**			Shales, clay, chalky clays		
	Toarcian	1976,9	2084,9			
	Middle-lower Lias	2074,1	2182,1			
TRIAS	**Rhetian**			Clay sandstones		
	Keuper (Grès de Chaunoy et Donnemarie)			Clay sandstones		

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For the Paris Basin case, two scenarios were considered (see Table 8.2), with the same geological target in the Dogger reservoir:

1. A main scenario: J-shape well with standard departure with a pipeline transport of CO_2 of about 3 km long from the CO_2 emitter
2. An alternative scenario: a long-deviated J-shape well without pipeline transport from the CO_2 emitter. The wellhead will therefore be located close to the emitter.

Table 8.2 Conceptual well data for the two scenarios of the French case

Item	Description	
Drilling Location	Seine-et-Marne	
	Deviated standard "J"-shape	Deviated long "J"-shape
	Max Incl : 25.88°- DLS: 3°/30 m	65° - 3°/30 m
	KOP: 380 m (30 m below surface casing shoe)	KOP: 124 mGL
Well Type	CO_2 (injector)	
Well Name & ID	PSTY-01	PSTY-02
Target Formation(s)	Oolithe Blanche Carbonates (Dogger - Bathonien)	
Depth reference	Ground Level (GL)	
Grid Coordinate System	RGF93 – Lambert 93	
Ground Level Elevation	+110 m MSL	+116 mMSL
Surface Location (Coordinates)	X: 695 658 m Y: 6 835 371 m	X: 696 247 m Y: 6 833 109
	UTM WGS84 48° 37' 6.556 N 2° 56' 25.2715 E	UTM WGS84 48° 35' 53.318N 2° 56' 54.1109 E
Target (Coordinates)	X : 695 643 m Y: 6 836 032 m UTM – WGS 84 Lat: 48° 37' 27.959 N – Long: 2° 56' 24.5202 E	
Target Depth	Top of Oolithe Blanche : 1765 mTVDSS	
Well Material	Tubing, casing and all equipment in direct contact with CO_2 will be made of specific material for CO_2 corrosion resistance. Dedicated studies will determine which is the best material (such as 13Cr, 22Cr, 25Cr alloys for steel for instance).	
Well TD - 10 m MD in Bajocien for logging pocket considerations	2212.50 mGL / 2046 mTVD/GL	4094 mMD/GL / 2046 m TVD/GL
Well Design lifetime	Commercial: 30 years	

8.1.1 Main scenario: standard J- shape well

This scenario considers a J-shape well with standard well departure towards the geological target and pipeline transport to bring the CO_2 from the emitter. The source of CO_2 is located about 3 km from the wellhead. The wellhead cannot be located at the vertical of the target due to surface constraints.

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8.1.1.1 Well profile

The well is planned as a deviated well, with a maximum inclination of 25.88° and a maximum dogleg severity (DLS) of 3°/30 m. The kick off point was chosen to be initiated in the second drilling phase, 30 meters below the surface casing shoe. The well is then maintained slanted at 25.88° towards the target and continues through until reaching TD which is planned in Bajocian (10 meters MD in the formation to accommodate for logging pocket).

The well departure is 744.3 meters (vertical section).

The top of targeted formation is reached slant and will cross the reservoir with the same inclination of ~26° which will provide improved contact length compared to a vertical well.

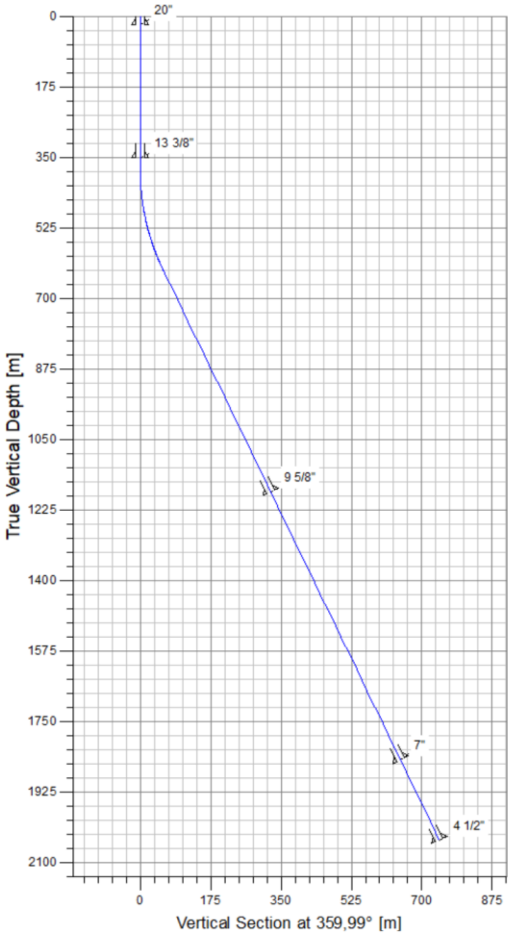

Figure 17 Standard J-shape trajectory for PSYT-01 well.

Design	MD (m)	CL (m)	Inc (°)	Azimuth (Grid) (°)	TVD GL(m)	DLS (°/30 m)	Build (°/30m)
Vertical	0 – 380	380	0	0	380	0	0
Build	380-639	259	25.9	360	630	3	3
Slant to TD	639 - 2211	1572	25.9	360	2045	0	0

Table 8.3 Main characteristics of the well trajectory for the main scenario of the French case

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The trajectory (Table 8.3) will be kicked off using mud motors and the rest of the well will be kept slant with motors BHAs. RSS are also an alternative for the directional work but are a more expensive solution.

8.1.1.2 Well Architecture

<u>Casing diameters and casing point selection:</u>

The well is designed from bottom to surface, starting with the requirements in CO_2 injection, to be able to cope with the flow rate while keeping the CO_2 in the supercritical state. The best compromise is to inject in a 4 ½” tubing (to get between 3.75 and 4” inside diameter).

As the objective of the well is to inject into the Oolithe Blanche with expected perforations between 1800 and 1840 m TVD SS (2061 to 2106m MD/GL), the reservoir section will be completed with a cemented liner that will be perforated in front of the zone of interest.

The production casing will be a 7’’ casing set at the top of the Lower Callovian or at the bottom of Upper Callovian (caprock) and cemented to surface.

The previous casing will be set after having crossed and covered the Albo Aptian aquifer and build up section. Based on the experience of the offset wells and geothermal wells in the Parisian Basin it will be set 10 m MD in the Portlandian formation; the casing diameter will be 9 5/8” and the casing will be cemented to surface. Thanks to this configuration, the Albo Aptian aquifer will be covered by 2 casings with cement up to surface.

The surface casing will be in 13 3/8” diameter and will allow the deepening of the well without BOP and will allow covering the shallow formations. It will be set to allow sufficient shoe strength for subsequent deepening of the well and according to limitations in collapse (if any).

A 20” conductor pipe will be set at ~30-40 m MD and cemented to surface during the platform construction phase.

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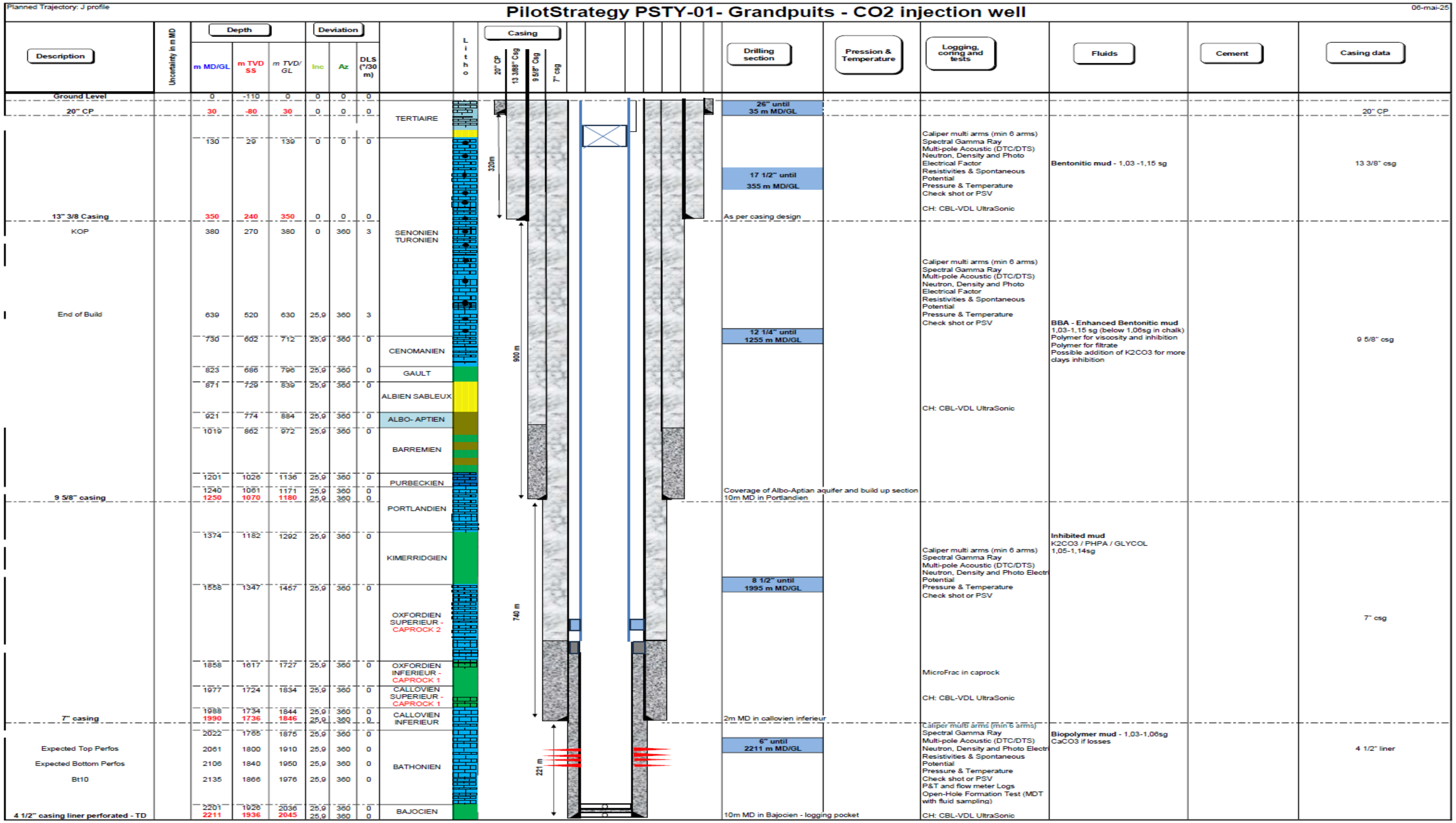

Figure 18: PSTY 01 Standard J profile well architecture diagram

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Table 8.4 Main characteristics of the completion for the main scenario of the French case

Size (OD)	OH	Casing	Shoe Depth (MD)	Weight	Grade	Connection	Purpose
20"	26"	Conductor	30-50 m	0.5 to 1 in	TBD	Welded	Structural Support Isolate surface waters and unconsolidated formations.
13-3/8"	17-1/2"	Surface	200-350 m	TBD	TBD	Buttress type	Isolate shallow formations -support for following drilling sections
9-5/8"	12-1/4"	Intermediate	1250 m	TBD	TBD	Buttress type	Isolate Intermediate Aquifers – technical casing
7"	8-1/2"	Production	1990 m	TBD	Specific CO_2 resistant for below packer	Premium	Production casing – Isolate Caprock
4-1/2"	6"	Liner	2211 m	TBD	Specific CO_2 resistant	Premium	Isolate reservoir and perform injectivity selection through perforations
4-1/2"	N/A	Tubing	1840 m	TBD	Specific CO_2 resistant	Premium	Injection tubing

8.1.2 Alternate Scenario: Deviated long J-shape well

This scenario considers a J-shape well with long well departure towards the geological target to place the wellhead close to the CO_2 emitter. This will limit the length of the CO_2 pipeline but requires extensive directional drilling.

8.1.2.1 J-shape well profile

The well is planned as a highly deviated J-shape well, with a maximum inclination of 65° and a maximum dogleg severity (DLS) of 3°/30 m, reached at 774 m MD/GL. The trajectory has been designed with a maximum inclination of 65°, therefore the kick off point was calculated at 124 m.

The target is reached with the long tangent section at 65° inclination and the well continues slant until reaching 10 m MD in the Bajocian formation at 4094 m MD / 2046 m TVD GL.

The departure of the well is 3340 m.

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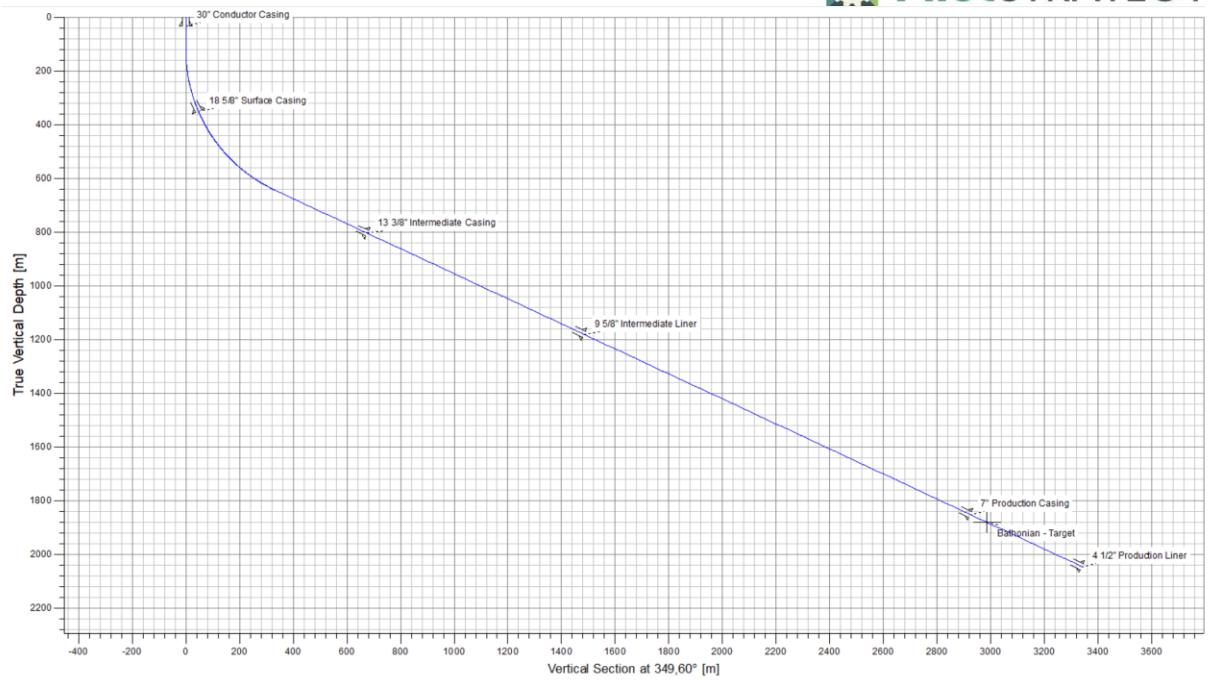

Figure 19 J-shape trajectory for PSYT-02 well.

Design	MD (m)	CL (m)	Inc (°)	Azimuth (Grid) (°)	TVD GL(m)	DLS (°/30 m)	Build (°/30m)
Vertical	0 – 124	124	0	0	124	0	0
Build	124-774	650	65	349,60	643,05	3	3
Slant to TD	774 - 4094	3320	65	349,60	2046	0	0

Table 8.5 Main characteristics of the well trajectory for the alternate scenario of the French case

The trajectory will be kicked off using mud motors and the rest of the well will be kept slant with motors BHAs. RSS are also an alternative for the directional work but are a more expensive solution. As the 8 ½" drilling section is planned to be a long section it is recommended to drill using RSS to improve the trajectory control and the hole quality and cleaning.

8.1.2.2 Well Architecture

Casing diameters and casing point selection:

The well is designed from bottom to surface, starting with the requirements in CO_2 injection, to be able to cope with the flow rate while keeping the CO_2 in the supercritical state. The best compromise is to inject in a 4 ½" tubing (to get between 3.75 and 4" inside diameter).

As the objective of the well is to inject into the Oolithe Blanche with expected perforations between 1800 and 1840 m TVD SS (3786 to 3880m MD/GL), the reservoir section will be completed with a cemented liner that will be perforated in front of the zone of interest.

The production casing will be a 7'' casing set at the top of the Lower Callovian or at the bottom of Upper Callovian (caprock) and cemented to surface. This casing can also be replaced by a liner but as it must cover the Albo Aptian formation to get 2 casings covering this aquifer, the gain to run a liner is limited.

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The previous casing will be set after having crossed and covered the Albo Aptian aquifer. Based on the experience of the offset wells and geothermal wells in the Parisian Basin it will be set 10 m MD in the Portlandian formation; the casing diameter will be 9 5/8" and the casing will be cemented to surface. Thanks to this configuration, the Albo Aptian aquifer will be covered by 2 casings with cement up to surface.

The previous casing will be an intermediate casing that will allow reducing the drilling section length. It is planned to set the casing shoe in the Gault Shales. This will be a 13 3/8'' casing.

The surface casing will be in 18 5/8" diameter and will allow the deepening of the well without BOP and will allow covering the shallow formations. It will be set to allow sufficient shoe strength for subsequent deepening of the well and according to limitations in collapse (if any).

A 30" conductor pipe will be set at ~30-40 m MD and cemented to surface during the platform construction phase.

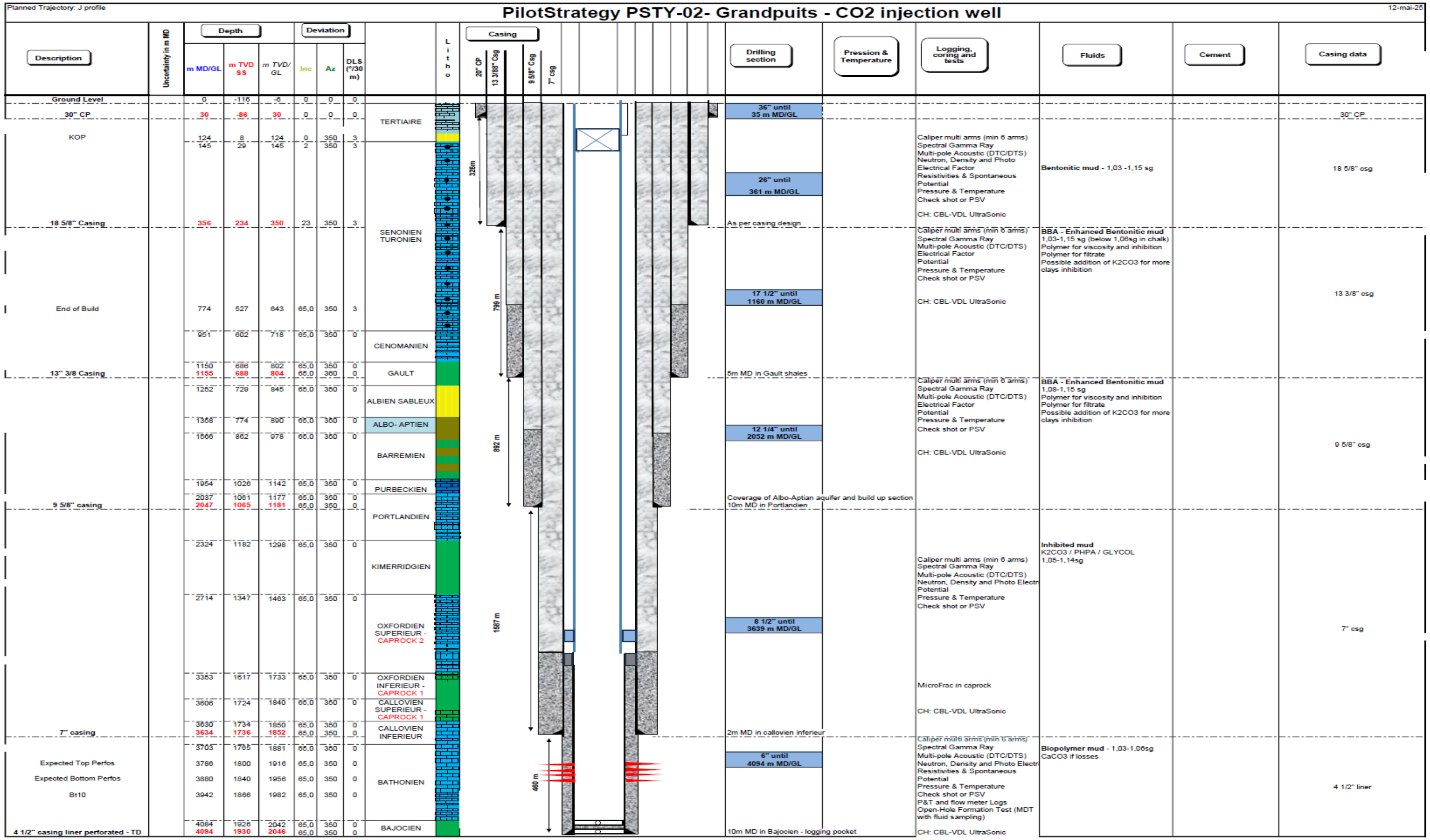

Figure 20: PSTY 02 Deviated long J profile well architecture diagram

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Table 8.6 Main characteristics of the completion for the alternate scenario of the French case

Size (OD)	OH	Casing	Shoe Depth (MD)	Section length	Weight	Grade	Connection	Purpose
30	36	Conductor	30-50 m	30-50 m	0.5 to 1 in	TBD	Welded	Structural Support Isolate surface waters and unconsolidated formations.
18 5/8”	26”	Surface	200-356 m	150-320m	TBD	TBD	Buttress type	Isolate shallow formations - support for following drilling sections
13-3/8”	17-1/2”	Intermediate	1155 m	799m	TBD	TBD	Buttress type	Deepening of the well
9-5/8”	12-1/4”	Intermediate	2047 m	892 m	TBD	TBD	Buttress type	Isolate Intermediate Aquifers – technical casing
7”	8-1/2”	Production	3634 m	1587 m	TBD	Specific CO_2 resistant for below packer	Premium	Production casing – Isolate Caprock
4-1/2”	6”	Liner	4094 m	460 m	TBD	Specific CO_2 resistant	Premium	Isolate reservoir and perform injectivity selection through perforations
4-1/2”	N/A	Tubing	4094 m	3484 m	TBD	Specific CO_2 resistant	Premium	Injection tubing

8.1.3 Well design considerations

Due to limited information on pore and fracture pressures, the selection of the casing shoe depth is primarily based on the well’s production casing objectives, as well as past drilling experience in both the oil & gas and geothermal sectors for both well scenarios.

8.1.3.1 Pore and fracture pressure

Limited data is available for the project. Some Formation Integrity Test (FIT) data from nearby oil and gas wells in the area are available, primarily for deeper formations such as the Toarcian and Sinemurian (Lower Jurassic or Lias).

It is important to note that, for these oil and gas wells, the Senonian/Turonian and Bathonian formations are considered loss zones. Additionally, more data on the Dogger formation will be provided from the SEIF 1 well, which is used for industrial water injection.

8.1.3.2 Tubular metallurgy

To address the corrosive environment expected during CO_2 injection periods, special steel (stainless steel) such as Chromium 13, 22 or 25 will have to be selected for the exposed casing sections and the injection tubing. These corrosion-resistant alloys provide enhanced durability and long-term

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performance under high-CO_2 conditions. The metallurgy and annular fluid should be designed to handle startup and shutdown conditions of the well.

The tubular sizes that will need to address this point are the 7” casing, 4-1/2” liner and the 4-1/2” tubing.

8.1.3.3 Cement

The cement quality is going to be a crucial factor in ensuring well integrity on the lower sections of the well to minimize leakage risks and preventing long-term deterioration due to the aggressive nature of CO_2, particularly in high-pressure conditions. The cement must be specifically designed to withstand CO_2’s effects, including carbonation, which can significantly weaken the cement over time.

Some cement available on the market are CorrosaCemen from Halliburton, EverCRETE from Schlumberger, just to name a few.

8.1.3.4 Completion and production design

Upper Completion: **4-1/2” Tubing String**

- **Size**: 4-1/2" OD, weight range to be assessed to get the most efficient inside diameter for CO_2 injection and to get sufficient margin in wall thickness to account for potential corrosion.
- **Metallurgy**: 13-25% Chromium to be specifically selected for the project
  - High mechanical strength (min 80 kpsi)
  - Suitable for CO_2 injection wells with high corrosion potential
  - Reduces integrity risks and material degradation over 20–30+ years of injection

Using a smaller tubing diameter will help:

- Maintain velocity and pressure of injected CO_2 (especially if gaseous or supercritical)
- Easier to manage thermal expansion and load calculations during injection shut-in/start-up cycles
- Faster and easier to run in-hole
- Reduces risk of equipment fatigue or buckling during installation
- Standardized across many service companies, ensuring equipment compatibility

Lower Completion: **4-1/2” Liner String**

- Size : 4-1/2” OD, Weight: TBD
- **Metallurgy**: 13-25% Chromium to be specifically selected for the project
  - High mechanical strength (min yield: 80 kpsi)
  - Suitable for CO_2 injection wells with high corrosion potential
  - Reduces integrity risks and material degradation over 20–30+ years of injection

Completion Additional Elements are summarized in Table 8.7.

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Table 8.7 Completion additional elements for the wells of the French case

Element	CO_2-Specific Requirements
Injection XMT & Wellhead	All components: CRA (Corrosion Resistant Alloy) Seal integrity: V0-rated gate valves and corrosion-resistant elastomers Penetrators: For control lines (TRSV), TEC lines (fiber optics), chemical injection
Permanent Packer	Metal-to-metal seals or CO_2-resistant elastomers (e.g., AFLAS, HNBR) V0-rated packers preferred for integrity With feedthrough ports for sensors or SCSSV lines
TRSV (Tubing-Retrievable Safety Valve)	Must be fail-safe closed, hydraulically operated, and CRA-lined Seals and springs must be CO_2-resistant V0-qualified TRSVs often required by regulation
Packer Fluid	Should be CO_2-compatible, non-corrosive, and thermally stable Typically brine-based fluids with corrosion inhibitors and possibly oxygen scavengers Avoid glycol-based fluids unless proven stable in CO_2
Bottom Hole Sensors	Quartz gauges or fiber-optic sensors for long-term reliability Installed above or below the packer
Fiber Optic Cable	Routed externally on tubing or integrated in clamp system Stainless or Inconel sheathed, gel-filled Requires penetrator through tubing hanger & packer feedthrough
Liner Hanger System	Compatible with CRA May include liner top packer if required for integrity Select hydraulic-set or mechanical-set types rated for CO_2
Tubing Hanger	Includes penetrators for TRSV and fiber optics Seals must be CO_2-resistant (metal or AFLAS/HNBR) Compatible with corrosion-resistant wellhead and XMT

8.1.4 Planned data acquisition

The objective of a data acquisition program is to reduce the subsurface uncertainties which might exist in the characterization of the targeted reservoir and its caprock for hosting the CO_2 storage. It will also bring new insights which will help verify the hypothesis, reservoir characteristics (volumes and connectivity) and the design basis of the project and thus reducing the potential exposition to the risks which could adversely impact the project development.

The objective of the wells is to collect as much data as possible on the geology of the area, specifically to assess the quality of the reservoir and evaluate the sealing and integrity of caprock. Therefore, wireline logging (open hole and cased hole) and coring will have to be conducted after each drilling phase, and the seal and reservoir rocks will be fully and continuously cored:

- The standard J-shape drilled well (PSTY-01) includes a “full and comprehensive set of logs”.
- Due to its strong inclination, the long J-shape drilled well (PSTY-02) will not be able to be logged by wireline tools. There is a considerable risk that the tools may either fail to descend

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or become irretrievably stuck within the hole. In this context, it will be advisable to conduct a minimal set of acquisitions during drilling (i.e. using Log While Drilling/LWD) to obtain key information in this well. Consequently, the long "J-shape" drilled well includes a "low to moderate set of logs by LWD" aimed at identifying the seal and reservoir intervals for correlation and slight characterization.

8.1.4.1 Mud logging

The mud logging acquisition must be operational from the first drilling section (if mud returns) to total depth (TD) of the well and perform the following tasks:

- Formation sampling and analysis (colour, grain size, sorting, grain shape, texture and fabric, hardness, cementation, grain composition, structure, accessories and inclusions, and porosity estimate) including descriptions (odour, visible staining, fluorescence intensity, percentage of sample fluorescing, speed of cut, natural light and fluorescence colour of cut, natural light residual colour).
- Gas sampling and analysis (FID total gas, FID chromatic analysis, background gas, circulation gas, connection and trip gas, Gas Ratio Analysis (GRA), data in the requested log format, H_2S detection (ditch gas line, active mud pits and shakers), continuous CO_2 detection, Dräger portable detector for H_2S, CO_2 and SO_2).
- Monitoring of drilling and mud parameters (depth, Rate of Penetration (ROP), Weight on Bit (WOB), rotary and bit Rotation Per Minute (RPM), mud pit levels, pumps strokes, lag time calculation, formation pressure analysis and prediction, drill string torque and drag, standpipe Pressure, mud density in/out).

Formation samples (cuttings) will be collected with a frequency of 5m in the seal and reservoir formations and at any other depth of interest previously determined. Additional spot samples will be taken upon reaching casing depth or when close to geological targets.

Regarding the drilled sections above the seal and the reservoir, the sampling frequency is subject to availability of mud returns and ROP. Taking samples, every 30 min is considered reasonable. If the ROP requires samples to be taken within a shorter time frame, there is a risk that the sampler catcher will not have enough time to collect and sort the cuttings properly. For this reason, it is recommended to limit the sampling frequency to 30 min for non-critical points (i.e. casing, formation changes).

8.1.4.2 Measurements while drilling (MWD)

Deviation surveys will be conducted during the drilling of the well. For the first drilling section, Totco shots can be sufficient, as the bottom-hole assembly (BHA) will be a rotary BHA, however MWD is recommended above all when it is required to kick off the well.

In the subsequent drilling sections, an MWD tool will be incorporated into the BHA, enabling the collection of inclination and azimuth surveys at regular intervals. The MWD system may also include Gamma-Ray logging while drilling, which will provide additional data to assist in the selection of the total depth (TD).

8.1.4.3 Logging while drilling (LWD)

No LWD is planned for the standard J Shape drilled well PSTY-01 (except GR as part of the MWD package).

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As the long J-shape drilled well PSTY-02 will most likely not be logged with wireline due to the strong inclination, a minimum level of data acquisition is required by LWD to ensure adequate subsurface evaluation. The minimum LWD requirement is Spectral Gamma Ray, Neutron, Density, Sonic and Resistivities along the seal and reservoir drilled sections.

8.1.4.4 Wireline logging (WL)

A full wireline logging acquisition (Table 8.8) is planned exclusively for the vertical drilled well PSTY-01.

The table below describes the wireline acquisition program per targeted drilled section. The Column "Log requirements" differentiates between acquisition types classified as mandatory (called "Must have") and those considered optional but potentially valuable for further analysis (called "Nice to have").

Table 8.8 Foreseen wireline acquisition for the main scenario of the French case

Acquisitions / data gathering	Open Hole (OH) or Cased Hole (CH)	Considered drilled section	Log requirements
Caliper multi arms (min 6 arms)	OH	All sections	Must have
Spectral Gamma Ray	OH	All sections	Must have
Multi-pole Acoustic (DTC/DTS)	OH	All sections	Must have
Neutron, Density and Photo Electrical Factor	OH	All sections	Must have
Resistivities & Spontaneous Potential	OH	All sections	Must have
Pressure & Temperature	OH	All sections	Must have
Check shot or PSV	OH	All sections	Must have
MicroFrac*	OH	Seal section	Must have
P&T and flow meter Logs	OH	Seal and reservoir sections	Must have
Open-Hole Formation Test (MDT with fluid sampling)	OH	Seal and reservoir sections	Must have
Nuclear Magnetic Resonance	OH	Seal and reservoir sections	Nice to have
Down-hole fluid sampling	OH	Seal and reservoir sections	Nice to have
Borehole Imagery	OH	Seal and reservoir sections	Nice to have
CBL, VDL, CCL and Ultra Sonic	CH	All cemented sections	Must Have
Wellpath Deviation & Azimuth	CH	All sections	Must Have

* To evaluate the minimum field stress and the hydrofracturing pressure in the seal formation, it is recommended to conduct frac-test in well. These tests will allow for checking the suitability and tightness of seal intervals.

8.1.4.5 Leak-off tests (LOT)

To be assess accordingly if required during the drilling phase of the well for deeper sections of the well. The LOT conducted during the last drilling phase, i.e. entry in the reservoir formation, is of critical significant and shall be accorded particular attention.

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8.1.4.6 Well testing

Well testing will be important to assess the fluids and initial injectivity of the well. It should initially be carried on the open section (DST or MDT dual packer) of the storage formation to confirm the injection interval. It would be important to confirm the injectivity with the final well completion to ensure the injectivity is preserved.

Prior to CO_2 injection, the initial injectivity tests will be carried out with brine, compatible with the storage brine to avoid scaling issues. Besides injectivity, the pressure buildup and fall-off will be carefully monitored for an extended period to assess the possible flow barriers in the storage formation.

8.1.4.7 Coring

The two wells PSTY-01 and PSTY-02 will be fully cored in the whole of seal and reservoir formation drilled sections. Due to the planned drilling diameter of 8 ½'' in the seal, the core diameter will be 4" in this section. In the reservoir section which will be drilled after setting the 7" casing, the core diameter will be 2" or 2,5".

A core spectral gamma ray shall be measured on cores to achieve accurate correlations between core measurements and those obtained from logging.

A core scan imaging shall be measured on cores to enable accurate bedding, fracture, and fault measurements.

8.1.4.8 Monitoring

The table below (Table 8.9) describes the planned monitoring program (at this stage) in specific formation intervals or in the whole interval of well. With an adapted program for acquisition, both wells, PSTY-01 and PSTY-02, can most likely be monitored. The Column "Requirements" differentiates between acquisition types classified as mandatory (called "Must have") and those considered optional but potentially valuable for further analysis (called "Nice to have").

Table 8.9 Planned monitoring acquisition for the pilot scenarios of the French case (pending confirmation from WP5)

Acquisitions	Requirements / Pilot and monitoring well	Considered formation interval
Fiber optic cable DAS	Must have	All
Borehole seismic (PSV)	Must have	All
Ultra Sonic (USIT)	Must have	Seal and reservoir intervals
Cement evaluation	Must have	Seal and reservoir intervals
Pulsed Neutron	Nice to have	Above porous aquifers and Reservoir sections
Borehole Electromagnetic	Nice to have	Reservoir
Annulars	Must have	
Micro seismic	Must have	

8.1.5 Computation of pressure and temperature variations within the wells

Prosper™ software[5] is used to compute the pressure and temperature changes within the injection tubing of the wells, PSTY01 and PSTY02.

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

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To meet the required injection pressure (Chassagne et al, 2024) and a temperature close to the reservoir temperature to minimize thermal expansion in the reservoir (Joule-Thomson effect), the well-head conditions are adjusted for each scenario as a function of the well design. The software computes the pressure increase along the well (VLP) so that the bottom hole pressure is above the injection reservoir pressure (IPR). The operating conditions are obtained at the intersection of the two curves VLP and IPR for a flow rate corresponding to the injection rate (300 kt/y ~439000 Sm^3/d).

8.1.5.1 Standard J-shape well: PSTY 01

The operating condition of the wells is illustrated in Figure 21. This corresponds to the following well-head conditions: P_{wh} = 96500 kPa and T_{wh} = 39.5 °C. At this stage of the design, due to the expected uncertainties in thermal and petrophysical properties of the reservoir and overburden formations, the operation windows approximate the expected gas rate. Such conditions lead to the following bottom conditions: P_{bh} =21115 kPa and T_{bh} = 62.4 °C.

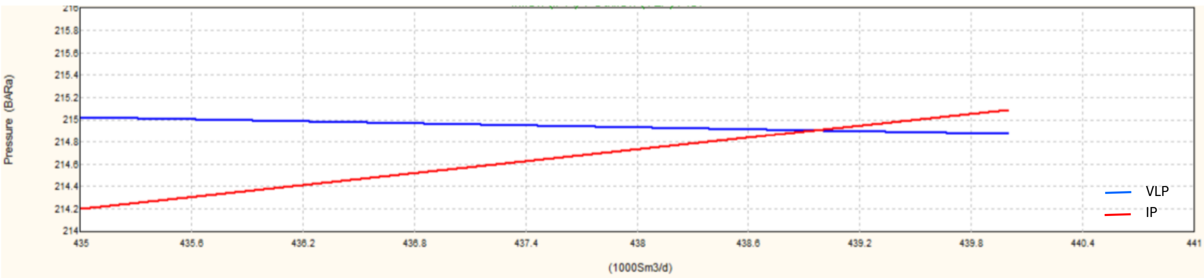

Figure 21 Operating conditions of the PSYT-01 well for the main scenario where IPR is the Inflow Performance due to. pressure in the reservoir, VLP is the Vertical Lift Performance due to. pressure in the well.

8.1.5.2 Long J-shape well: PSTY 02

This scenario considers a long deviated well and no pipeline transport as the wellhead is located within the emission plant premises.

The operating condition of the wells is illustrated in Figure 22. This corresponds to the following well-head conditions: P_{wh} = 12500 kPa and T_{wh} =56.4°C. At this stage of the design, due to the expected uncertainties in thermal and petrophysical properties of the reservoir and overburden formations, the operation windows approximate the expected gas rate. Such conditions lead to the following bottom conditions: P_{bh} =20500 kPa and T_{bh} = 62.1 °C.

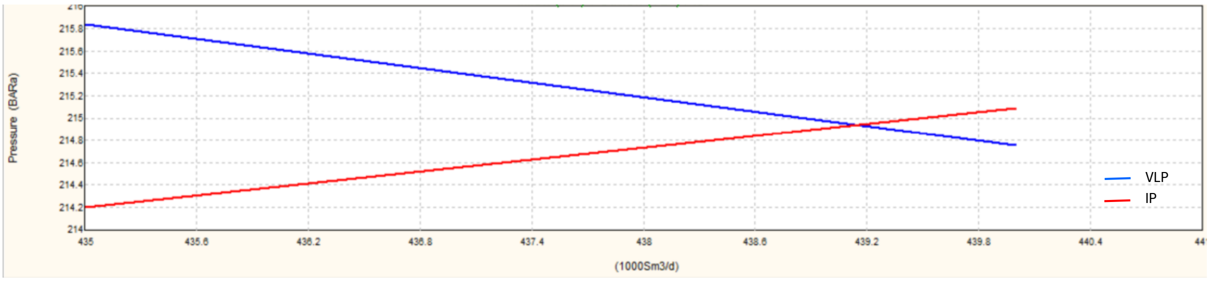

Figure 22 Operating conditions of the PSYT-02 well for the alternate scenario where IPR is the Inflow Performance due to. pressure in the reservoir, VLP is the Vertical Lift Performance due to. pressure in the well.

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8.2 Lusitanian Basin (Portugal)

A comprehensive analysis of the reception and injection facilities required for the Lusitanian Basin project is here described, focusing on both the Pilot and Commercial phases. The design and implementation of these facilities are critical to ensuring the efficient and safe storage of CO_2. This analysis excludes the well design, drilling, and completion processes, which are currently in progress. For further information about Lusitanian Basin storage concept and main considerations see Deliverable 4.3 "Final concept description and preliminary consideration by regions" (Canteli, 2025b).

8.2.1 Pilot Phase

For the pilot phase of the Lusitanian Basin project, the receiving hub is strategically located at Figueira da Foz Port, facilitating the transport and storage of CO_2 before offshore injection. The hub includes loading/unloading infrastructure, designed to efficiently transfer CO_2 tanks directly to a ship. The loading and unloading infrastructure comprise ancillary equipment essential for the transfer of CO_2 to the transport vessels. The design must ensure compatibility with shipping vessels, robust safety measures, and flexibility to accommodate varying CO_2 volumes at a medium pressure, dense phase. Collaborative efforts are being made together with the CTS project (EU-funded project) to understand the available solutions for direct carbon injection, aligning with PilotSTRATEGY's basis of design.

The offshore facilities for shipping CO_2 consist of onboard injection pump, heater system, and injection wells. These components are critical for injecting CO_2 into the storage reservoir at the required pressure and temperature. Design considerations include efficient injection rates, monitoring systems, and scalability for the commercial phase. The injection wells will be designed to manage the required pressures and temperatures for CO_2 storage, ensuring long-term stability and safety of the reservoir.

The design of permanent infrastructure for the Figueira da Foz hub is driven by the specific properties of CO_2 and the operational handling requirements. The intermediate hub's primary role shifts to offloading and transfer of dense-phase CO_2 for offshore transport and injection. This reduces energy demand at the hub and eliminates the need for liquefaction facilities, allowing for more compact and cost-efficient terminal design. Key technical specifications of permanent components at a coastal intermediate hub configured for handling CO_2 reflect best practices in industrial-scale CCS projects (e.g. DNV GL; IEAGHG, 2021; Northern Lights; Porthos; GreenSands; IEA) and account for operational safety, and the need to maintain CO_2 in a stable dense phase under varying conditions of flow and pressure. The facilities are designed to be scalable, allowing for easy expansion as the project transitions to the commercial phase.

Making CO_2 injection facilities work well relies on following detailed technical guidelines. These guidelines make sure that all parts, from the wellhead to manifold systems, work properly under different pressure and temperature conditions. Key features like pressure relief valves, leak detection systems, and emergency shutdown procedures are crucial for keeping operations safe and efficient. Also, using materials that resist CO_2 corrosion is essential to prevent wear and tear and to ensure the facilities last a long time. The design is flexible, so the facilities can be easily expanded when moving from pilot to commercial phases.

We've put together these technical specifications based on industry standards and the best practices from leading projects, as well as considering general guidelines set in deliverable D4.4 (Valderrama et al., 2024). The specs for wellhead, manifold systems, and injection wells include insights from sources like the Baker Hughes MS-TTL System, SPE CCS Resources, and other technical references from OGCI and IOGP (Table 8.10).

Table 8.10 Technical specifications for wellhead, manifold systems (based on Baker Hughes MS-TTL System; SPE CCS Resources; Sotoodeh, 2020), and injection wells (Northern Lights CCS project; DNVGL – CO2 Well Integrity Guidelines; IEAGHG reports

Component	Specification	Details
Wellhead	*Pressure & Temperature Ratings*	Up to 10,000 psi; API Temperature Class K (-60°C)
	Sealing Mechanisms	Metal-to-metal seals (e.g., MS-TTL system)
	Safety Features	Surface-Controlled Subsurface Safety Valves (SCSSVs); Non-Return Valves (NRVs)
	Monitoring & Control	Subsea Control Modules (SCMs); Pressure and Temperature transducers (UPT, DPT)
Manifold	*Flow Control Components*	Retrievable modules with actuated valves, choke valves, flow metering
	Material Selection	CO_2-resistant alloys like 22Cr duplex stainless steel
	Pressure Rating & Standards	Typically, 250 bar; Designed per ASME B16.25 and related subsea standards
	Modularity & Maintenance	Modular design allows scalable configuration and easier intervention
Injection Wells	*Casing and Tubing Materials*	Corrosion-resistant alloys (CRA) like Inconel or 13Cr steel to withstand CO_2 exposure
	Well Integrity Features	Cemented annuli, pressure monitoring, and zonal isolation (e.g., packers)
	Monitoring Systems	Downhole sensors (temperature, pressure, flow); fiber-optic DAS/DTS for real-time surveillance

During the pilot-scale phase no permanent infrastructure will be built at the Figueira da Foz port, with the ship and train tanks providing the storage capacity during the loading and offloading stages.

8.2.2 Commercial Phase

The permanent receiving hub for the Commercial Phase of the Lusitanian Basin project would be the result of an expansion from the Pilot Phase at the Figueira da Foz coastal port, or in the near vicinity of it, probably in the southern margin of the Mondego river. These upscaled facilities repressurizing and pipeline infrastructure and an auxiliary heating system, connected to the pipeline infrastructure.

The pipeline infrastructure would transport dense-phase CO_2 from the onshore hub and recompressing unit to the offshore injection site. The design of the pipelines considers factors such as pipeline diameter, material selection, and corrosion protection to ensure long-term reliability. For the moment, the subsea wellhead, manifold and injection well specifications should be the same as considered for the Pilot Phase.

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Table 8.11 – Main permanent facilities to be considered at the Figueira da Foz Port (based on DNVGL-RP-J203 Carbon Dioxide Transport – Recommended Practice; Porthos CCS Project, Northern Lights CCS Project, GreenSands, IEA CCS Technical Reports; OGCI CCUS Hub Concept Reports)

Component	Function	Details
Injection Pump	Boosts pressure of incoming medium pressure CO_2 to match offshore pipeline pressure	High-pressure pumps, flow control valves, surge protection
CO_2 Pipeline Launch Station	Interface facility where CO_2 is introduced into the offshore pipeline	Pig launchers, metering systems, isolation valves, emergency shut-down (ESD) systems
Utility Systems	Support systems for all processing and safety operations	Power supply, cooling water, nitrogen system, HVAC, drainage, and firefighting systems
Control Room & SCADA System	Manages operations of all on-site units and interfaces with offshore systems	Real-time monitoring, control interfaces, alarm systems, safety instrumentation
Safety & Environmental Systems	Ensures compliance with health, safety, and environmental (HSE) regulations	Gas detection, flare system, emergency response, containment basins, and vent stacks

The design considerations for the permanent receiving hub at Figueira da Foz during the commercial phase include long-term compatibility with pipeline transport, advanced safety and monitoring systems, and high-capacity CO_2 handling. The facilities are designed to handle the increased CO_2 volumes and pressures associated with pipeline transport, with appropriate materials and components selected to withstand the operating conditions. Booster units must accommodate CO_2's unique thermodynamic properties, especially its cooling effects during phase transitions.

Advanced safety and monitoring systems, including pressure relief valves, leak detection systems, temperature sensors, and real-time monitoring of CO_2 flow and storage conditions, are implemented to ensure the safe operation of the facilities – all design aspects must align with national and international safety, environmental, and CCS-specific standards such as ISO 27913 and DNV practices. Safety layouts should include emergency shutdown and overpressure protection.

8.2.3 Summary of cost structure for Reception and Injection Facilities

The cost structure breakdown for the Pilot and Commercial phases, summarized in Table 8.12, provides a snapshot of current facility estimates.

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Table 8.12 Summary of Class V estimated CAPEX and OPEX for Pilot (railway and shipping) and Commercial (pipeline) phases.
¹ – to be confirmed

		Component	CAPEX (M€)	OPEX M€/ Year	Total OPEX over 3 years	Total 3-Year Cost	Total OPEX over 30 years	Total 30-Year Cost
Pilot	***Railway***	CIMPOR (Souselas)	1,5	0,50	1,5	3,0		
	Figueira da Foz Hub	Onshore CO_2 Hub (Port Terminal)	6	1,2	3,6	9,6		
	Shipping	CO_2 Carrier (including a used, small-scale skip, two storage tanks 800-1000 m^3)	9	7	21	30,0		
		Injection pumps and offloading hose for connection to well	20[1]			20,0		
		Injection Well + Subsea Manifold	30	8	24	54,0		
		Control Systems, Power Supply	5			5,0		
	TOTAL	***Pilot Phase***	***72***	***17***	***50***	***122***		
Commercial	***Onshore Pipeline***	CIMPOR (Souselas)	27,7	1,5			40,5	68,2
	Figueira da Foz Hub	Injection Pump	5	0,5			13,5	18,5
	Offshore Pipeline	Offshore Pipeline	24	1,5			40,5	64,5
		Injection Well + Subsea Manifold		8			216	216
		Maintenance and Monitoring	5	1			27	32
	TOTAL	***Commercial Phase***	***62***	***13***			***338***	***339***

** Annualized value for 3 years, considering a total CAPEX of ~12 €M and a locomotive and wagons lifespan of 25 years.*
***Annualized value for 3 years, considering a total CAPEX of ~51 €M and a ship lifespan of 25 years.*

The cost structure for the reception and injection facilities provides a comprehensive financial overview essential for understanding the project's economic feasibility. Based on the transport options and case assumptions, the Pilot Phase is now estimated to have a CAPEX of €72 million, and OPEX of €50 million, over the course of 3 years. The onshore facilities at the Figueira da Foz port, which includes loading/unloading infrastructure and landfall construction to accommodate ship docking, as well as the carrier shipping operation and injection facilities are the main cost drivers for this phase. The Commercial Phase estimates a total CAPEX of €62 million and OPEX of €338 million, over the course of 27 years. The pipeline construction (and maintenance) and the temporary storage unit at Figueira da Foz terminal are the main cost drivers, even with the auxiliary support infrastructure already in place at the port. Notice that in the Commercial Phase it is not included the cost of the injection well and subsea manifold that were assigned entirely to the Pilot Phase, albeit the possibility of having used annualized costs.

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As these options mature and further optimizations are made, the costs and logistical details are subject to adjustment. This ongoing refinement process will ensure that the best strategies are adopted for the Lusitanian Basin project, particularly for the Commercial Phase, ultimately leading to more efficient and cost-effective solutions.

8.3 Ebro Basin (Spain)

For further information about Ebro storage wells and facilities see Deliverable 4.3 "Final concept description and preliminary consideration by regions" (Canteli, 2025b).

8.3.1 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.

Table 8.13 2 Mt scenario expenditures summary

TOTAL CAPEX (M€)	16.04
OPEX (M€/y)	2.43
TOTAL ABEX (M€)	3.13

8.3.2 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 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 305 barg.

Table 8.14 27 Mt scenario expenditures summary

TOTAL CAPEX (M€)	37.90
OPEX (M€/y)	6.60
TOTAL ABEX (M€)	6.87

8.3.3 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 23 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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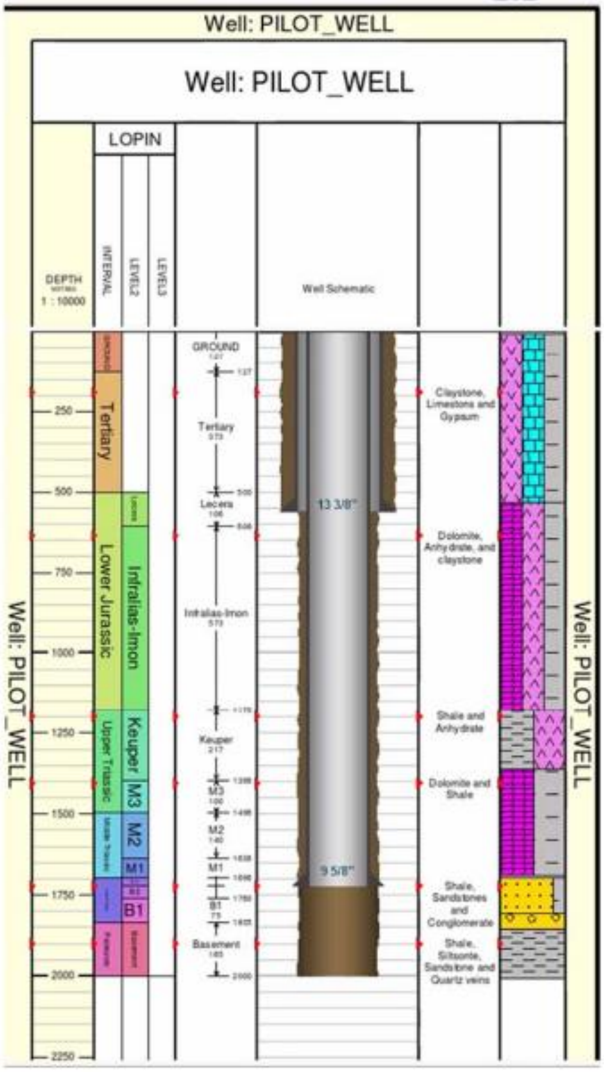

Figure 23 Lopin area vertical well first draft

8.3.4 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).

8.4 Upper Silesia Basin (Poland)

8.4.1 CO_2 reception infrastructure at the injection site

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

Main components of the CO_2 injection terminal:

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- CO_2 receiving station – equipped with buffer tanks, gas analyzers to verify CO_2 purity (e.g., H_2O, H_2S content);
- CO_2 conditioning and regulation station to adjust the physical properties of injected CO_2 (pressure and temperature of geological formation) including heat exchangers, pressure equalization systems, additional CO_2 compressors;
- safety and emergency pressure relief systems to manage overpressure and operational incidents (high-pressure safety valves and venting lines, shut-off valves, gas leak detectors);
- injection high-pressure wellheads for directing CO_2 into one or more wells, including instruments for flow rate, temperature and pressure control;
- monitoring wells for pressure monitoring in the reservoir, early detection of CO_2 migration, periodic sampling of gases or groundwater;
- supporting installations such as system for real-time monitoring and remote operation, backup power supply (UPS and diesel generators), telecommunications and security systems.

8.4.2 Well design

The main elements of the installation in terms of CO_2 storage will be: injection well(s), test wells and injection station. The number of injection wells necessary to achieve the required injection rate will ultimately depend on the hydrogeological parameters of the aquifers, the selected region, the number of brine levels captured by one well and their depth, as well as the amount of carbon dioxide injected over time.

The study nature of this work, combined with the lack of possibility to conduct in situ tests and tests of initial CO_2 injection, make it impossible to propose specific grids for the location of injection, test and test wells.

Due to the relatively small amounts of CO_2, it was assumed that injection will take place through one injection well. The accompanying monitoring and test wells will be located on the periphery of the potential CO_2 storage site.

Thus, the need to drill one injection well and several research and observation wells is initially assessed. Depending on the injection process and observed phenomena, further wells will have to be drilled. Their number should also be determined during previous model tests.

In the case of using the variant with at least three geological wells, then used for research and observation purposes (during the injection test), the following objectives will be achieved:

- significantly better recognition of geological conditions, especially regarding the regularity of deposition, thickness and continuity of collector layers and insulating layers,
- the possibility of a precise examination of the CO_2 absorption and permeability of the geological structure and the surrounding insulating rocks,
- examination of the speed and range of CO_2 penetration in the porous medium of the geological structure, with appropriate arrangement of research and observation wells,
- examination of storage stability or decrease in CO_2 content as a function of time, which would indicate an existing breakthrough or slow leakage of the injected gas.

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The carbon dioxide pipeline will be led to the final injection point, which will be equipped with a collection manifold, acting as a pressure buffer. This manifold will be connected to the injection holes by an internal pipeline network, in which multi-stage pressure reducer stations will be built. The issue of the need to reduce the pressure required for injection results from the absorbency parameters of the deposit. In order to ensure optimal injection conditions, it may also be necessary to build a carbon dioxide heater station. The final element of the carbon dioxide injection installation will be the borehole heads and their downhole equipment (injection and casing pipes, hydraulic packers, perforation intervals, and others). When designing the injection holes, it is necessary to take into account the places in the injection perforation intervals for installing sensors and devices for periodic monitoring of the processes occurring at the bottom of the injection holes. A typical comprehensive CO_2 injection installation should include the following equipment:

- collection manifold,
- pressure reducer station (multi-stage),
- transfer pump,
- CO_2 heating system (depending on the final CO_2 parameters),
- system of pipe connections with the borehole head,
- set of sensors and measuring equipment for the installation in combination with the control and monitoring system.

The selection of detailed installation parameters will depend on the state of the supplied medium, its quantity, temperature, and above all the final pressure.

CO_2 injection well and wellhead configuration

The number of wells required for a storage project will depend on a number of factors, including total injection rate, permeability and thickness of the formation, maximum injection pressures and availability of land-surface area for the injection wells. In general, fewer wells will be needed for high-permeability sediments in thick storage formations and for those projects with horizontal wells for injection. For example, the Sleipner Project, which injects CO_2 into a high-permeability, 200-m-thick formation, uses only one well to inject 1 $MtCO_2$/yr (Korbol and Kaddour, 1994). In contrast, at the In Salah Project in Algeria, CO_2 was injected into a 20-m-thick formation with much lower permeability (Riddiford et al., 2003). Here, three long-reach horizontal wells with slotted intervals over 1 km are used to inject 1 $MtCO_2$/yr. Cost will depend, to some degree, on the number and completion techniques for these wells. Therefore, careful design and optimization of the number and slotted intervals is important for cost-effective storage projects.

An injection well and a wellhead are depicted in Figure 24. Injection wells commonly are equipped with two valves for well control, one for regular use and one reserved for safety shutoff. In acid gas injection wells, a downhole safety valve is incorporated in the tubing, so that if equipment fails at the surface, the well is automatically shut down to prevent back flow. Jarrell et al. (2002) recommend an automatic shutoff valve on all CO_2 wells to ensure that no release occurs and to prevent CO_2 from inadvertently flowing back into the injection system. A typical downhole configuration for an injection well includes a double-grip packer, an on-off tool and a downhole shutoff valve. Annular pressure monitors help detect leaks in packers and tubing, which is important for taking rapid corrective action. To prevent dangerous high-pressure buildup on surface equipment and avoid CO_2 releases into the atmosphere, CO_2 injection must be stopped as soon as leaks occur. Rupture disks and safety valves

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can be used to relieve built-up pressure. Adequate plans need to be in place for dealing with excess CO_2 if the injection well needs to be shut in. Options include having a backup injection well or methods to safely vent CO_2 to the atmosphere.

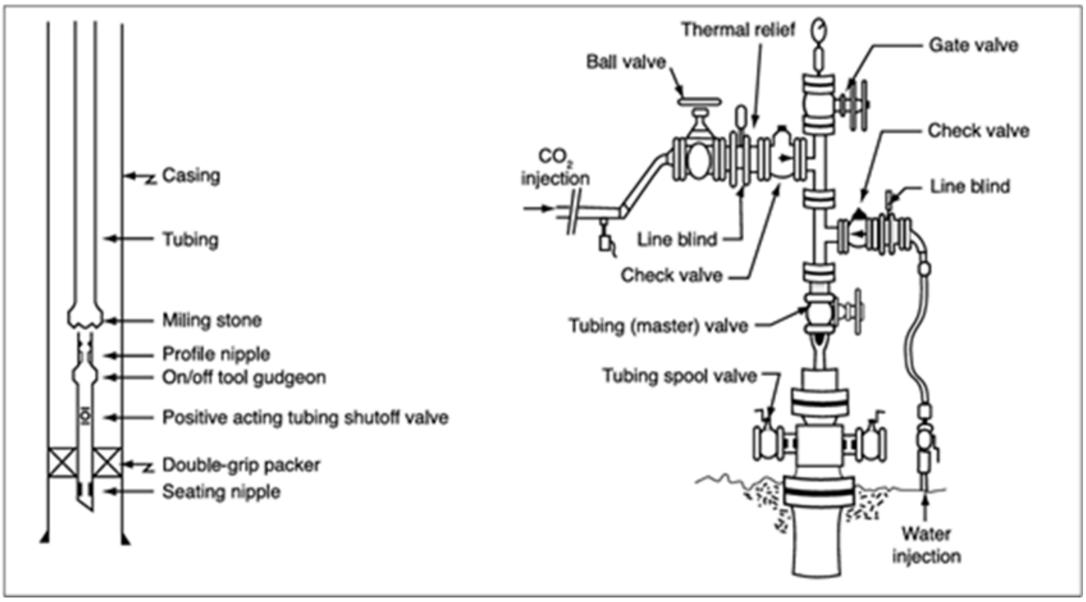

Figure 24 Typical CO2 injection well and wellhead configuration (IPCC, 2018)

Proper maintenance of CO_2 injection wells is necessary to avoid leakage and well failures. Several practical procedures can be used to reduce probabilities of CO_2 blow-out (uncontrolled flow) and mitigate the adverse effects if one should occur. These include periodic wellbore integrity surveys on drilled injection wells, improved blow-out prevention (BOP) maintenance, installation of additional BOP on suspect wells, improved crew awareness, contingency planning and emergency response training (Skinner, 2003).

For CO_2 injection through existing and old wells, key factors include the mechanical condition of the well and quality of the cement and well maintenance. A leaking wellbore annulus can be a pathway for CO_2 migration. Detailed logging programs for checking wellbore integrity can be conducted by the operator to protect formations and prevent reservoir cross-flow. An injection well (Figure 1) must be equipped with a packer to isolate pressure to the injection interval. All materials used in injection wells should be designed to anticipate peak volume, pressure and temperature. In the case of wet gas (containing free water), use of corrosion-resistant material is essential.

The design of a CO_2 injection well is very similar to that of a gas injection well in an oil field or natural gas storage project. Most downhole components need to be upgraded for higher pressure ratings and corrosion resistance. The technology for handling CO_2 has already been developed for EOR (enhanced oil recovery) operations and for the disposal of acid gas. Horizontal and extended reach wells can be good options for improving the rate of CO_2 injection from individual wells. The Weyburn field in Canada is an example in which the use of horizontal injection wells is improving oil recovery and increasing CO_2 storage. The horizontal injectors reduce the number of injection wells required for field development. A horizontal injection well has the added advantage that it can create injection profiles that reduce the adverse effects of injected-gas preferential flow through high-permeability zones.

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Development of technical assumptions for the design and construction of CO_2 injection installations

The suitability of a site for carbon dioxide storage is a function of three fundamental technical factors:

- the effectiveness of the sealing layers in preventing the migration of CO_2 to the surface,
- the suitability of the reservoir for injection,
- the volumetric capacity of the reservoir for storing the injected CO_2.

The main element of the installation in terms of CO_2 storage will be the injection well(s), monitoring wells and the injection station. The number of injection wells necessary to achieve the required injection intensity will depend on the hydrogeological parameters of the aquifers, the selected region, the number of aquifers taken from one hole and their depth.

The minimum variant should assume drilling:

- one injection well (depending on the region and the number of levels taken), the target diameter of which will be approximately 7",
- one research and control well with a diameter of approximately 4".

It should be expected that this will not be the final number of wells, and depending on the flow rate and observed phenomena, further boreholes will have to be drilled. Their optimal number will be determined in the course of further work and in situ research.

Ultimately, drilling research and injection wells will allow for:

- precise identification of geological conditions, especially the presence, thickness and continuity of collector layers and insulating layers, compared to the current recognition,
- precise examination of the absorption and permeability of the geological structure and the surrounding insulating rocks,
- examination of the rate and range of CO_2 penetration in the porous medium of the geological structure, with appropriate distribution of injection boreholes,
- examination of storage stability; in the event of a decrease in CO_2 content over time, this may indicate a loss of tightness by the reservoir and a slow gas leakage.

Drilling of injection boreholes should be carried out using sectional coring, mainly of the reservoir series and sealing layers in the roof and floor of the collector. The obtained cores will allow for laboratory and model tests in terms of capacity, absorption and permeability.

CO_2 storage locations should be treated as absolutely preliminary; they should be preceded by possibly comprehensive geophysical studies in order to determine, first of all, the thickness and tightness of the overburden and to investigate possible CO_2 migration paths, with particular emphasis on possible fault zones.

Considering that during geological storage there are no two identical or even similar places, even in the same geological formation, there are also no clear recommendations as to the techniques or

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monitoring tools used. However, the following techniques should be considered and should be used if the necessary data characterizing the storage site were provided:

- monitoring of pressure, temperature and chemical composition inside the reservoir at the injection point and the zone above,
- vertical seismic profiling,
- seismic surveys (3D and 4D),
- use of tiltmeters, InSAR and other instruments for detecting surface deformation,
- microseismic monitoring,
- soil/air monitoring.

Injection Operation Guidelines

There are several important issues to consider when planning and implementing CO_2 injection into a geological structure. The above-mentioned activities are included in the injection operation guidelines, in which:

1. The site development plan for the injection facility should be developed sufficiently early – still in the permit application phase.

2. The facility supervision should develop a transparent operation plan and work schedule with sufficient flexibility in the use of operation data and new information from measurements, monitoring and verification to be able to adapt to unexpected situations in the underground environment.

3. The operation plan should be based on information characterizing the injection site and on a risk assessment; it should include strategies for preventing/reducing the effects of unforeseen situations.

4. The injection supervisor should plan the actions in case of compressor failure in connection with the CO_2 supply agreements, backup facilities, storage space and, if necessary, CO_2 release permits in specific situations.

5. The wells and installations should be appropriately selected for the operating conditions and meet the standards and approvals specified in the currently applicable relevant industry regulations regarding design and construction.

6. The reservoir and risk models should be periodically calibrated (verified) based on operational data and repeated flow simulations. In the event of significant changes in the expected or actual geological situation, immediate actions should be taken to adjust the operating parameters of the installation.

7. Cementing of the external borehole casing should be performed from the injection zone at least up to the zone above the impermeable layers.

8. Well integrity, including the location of well cementing and the injection zone, should be checked after completion of borehole development and routinely during operation – in accordance with applicable regulations.

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9. Tests and trials related to trial injection of various media (e.g. water – *water injection tests*) should be carried out in all prospective CCS locations.

10. Injection pressure and efficiency should be determined using geomechanical analysis of the well. The principles should not be generalized, but rather individualized depending on the prevailing local conditions.

11. Installation supervision should follow established health and safety rules for sites exposed to direct contact with CO_2.

12. Supervision should follow the rules of work applicable in environments highly exposed to corrosion, and in particular periodically check devices, boreholes, measuring instruments. Detected corrosion should be immediately neutralized and damaged equipment components should be replaced. Unless special metals are used, equipment in the injection zone should not come into contact with water to prevent corrosion.

13. Operational data should be recorded and saved throughout the process and integrated with reservoir modeling and simulations.

14. Collected data should be used to mark individual stages of project implementation and anticipated simulations.

CO_2 injection well design

The typical components of an injection well that are relevant to maintaining mechanical integrity and to ensuring that fluids do not migrate from injection zone into underground sources of drinking water (USDW) are the casing, tubing, cement and packer (Figure 25). The well components should be designed to withstand the maximum anticipated stress in each direction - axial direction (tensile, compressive) or radial (collapse, burst), and include a safety factor. The loading in each of the stress directions should be compared to the strength of the material in that direction. The loadings correspond to the burst, collapse, and tensile strengths of the material.

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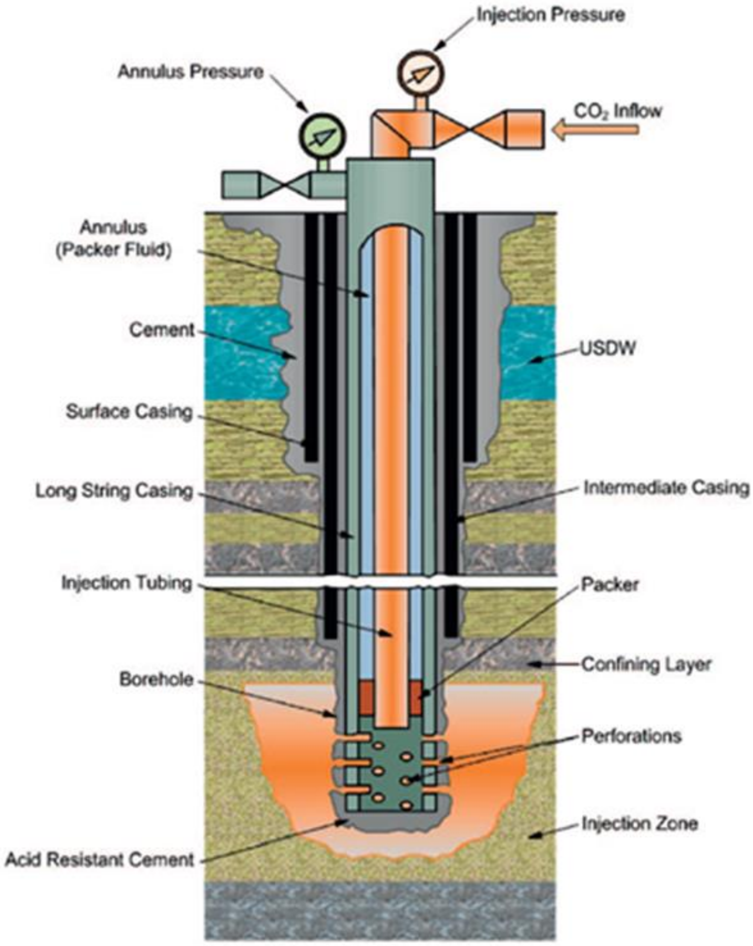

Figure 25 Schematic of a CO2 injection well (Gaurina-Medimurec, 2011)

An injection well typically consists of one or more casings. Leaks in the casing can allow fluid to escape into unintended zones or allow fluid movement between zones. The construction materials selected for the casing and the casing design must be appropriate for the fluids and stresses encountered at the site-specific down-hole environment. CO_2 in combination with water forms carbonic acid, which is corrosive to many materials. Native fluids can also contain corrosive elements such as brines and hydrogen sulfide. In CO_2 injection wells, the spaces between the long string casing and the intermediate casing, and between the intermediate casing and the surface casing as well as between the casings and the geologic formation are required to be filled with cement, along all casings.

The tubing runs inside the long string casing from the ground surface down to the injection zone. The injected fluid moves down the tubing, out through the perforations in the long string casing, and into the injection zone. The tubing ends at a point just below the packer. The space between the long string casing and tubing must be filled with a non-corrosive packer fluid. The tubing forms another barrier between the injected fluid and the long string casing. It must be designed to withstand the stresses and fluids with which it will come into contact. The tubing and long string casing act together to form two levels of protection between the carbon dioxide stream and the geologic formations above the injection zone. A safety valve/profile nipple can be used to isolate the wellbore from the formation to allow the tubing string to be replaced. Injection will be conducted through the perforated casing. In the base case there is no stimulation method used, but hydro fracturing may be an option. Using acids to improve injectivity is not recommended because of the possible damage to the cement sheath and casing.

Cement is important for providing structural support of the casing, preventing contact of the casing with corrosive formation fluids, and preventing vertical movement of carbon dioxide. Some of the most current researches indicate that a good cement job is one of the key factors in effective zonal isolation. The proper placement of the cement is critical, as errors can be difficult to fix later on. Failing to cement the entire length of casing, failure of the cement to bond with the casing or formation, not centralizing the casing during cementing, cracking, and alteration of the cement can all allow migration of fluids along the wellbore. If carbon dioxide escapes the injection zone through the wellbore because of a failed cement job, the injection process must be interrupted to perform costly remedial cementing treatments. In a worst-case scenario, failure of the cement sheath can result in the total loss of a well. During the injection phase, cement will only encounter CO_2. However, after the injection phase and all the free CO_2 around the wellbore is dissolved in the brine, the wellbore will be attacked by carbonic acid (H_2CO_3). The carbonic acid will only attack the reservoir portion of the production casing, therefore special consideration of CO_2-resistant cement needs only to be considered for the reservoir, primary seal and a safety zone above the reservoir. Regular cement should be sufficient over the CO_2-resistant cement. However, since two different cement slurries will be used, CO_2-resistant cement that is compatible with regular Portland cement has to be used to prevent flash setting. The cement must be able to maintain a low permeability over lengthy exposure to reservoir conditions in a CO_2 injection and storage scenario. Long-term carbon sequestration conditions include contact of set cement with supercritical CO_2 (>31°C at 73 bars) and brine solutions at increased pressure and temperature and decreased pH (Kutchko et al., 2007).

A packer is a sealing device which keeps fluid from migrating from the injection zone into the annulus between the long string casing and tubing. The tubing is set on a retrievable packer above the injection zone to ease the changing of the tubing if pitting is identified during regular inspections. A packer must also be made of materials that are compatible with fluids which it will come into contact.

Design requirements

All new CO_2 injection wells have to be cased and cemented to prevent the migration of fluids into or between underground sources of drinking water. The casing and cement used in the construction of each newly drilled well has to be designed for the life expectancy of the well. In determining and specifying casing and cementing requirements, the following factors has to be considered: (1) depth to the injection zone; (2) injection pressure, external pressure, internal pressure, axial loading, etc.; (3) hole size; (4) size and grade of all casing strings (wall thickness, diameter, nominal weight, length, joint specification, and construction material); (5) corrosiveness of injected fluids and formation fluids; (6) lithology of injection and confining zones; and (7) type and grade of cement. The following information concerning the injection zone has to be determined or calculated for new wells: (1) fluid pressure; (2) fracture pressure; and (3) physical and chemical characteristics of the formation fluids.

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Appropriate logs and other tests have to be conducted during the drilling and construction of new wells (Gaurina-Međimurec, Pašić, 2011). Mandatory technical requirements for CO_2 injection well are presented in Table 8.15 Mandatory technical requirements for CO2 injection well (NETL, 2009).

Technical Requirements for CO_2 Injection Well (Class VI)	
Site characterization	Extensive site characterization needed, including well logs, maps, cross-sections, USDW locations, determine injection zone porosity, identify any faults, and assess seismic history of the area.
Fluid Movement	No fluid movement to the underground sources of drinking water (USDW).
Area of Review (AoR)	Determined by computational model and reevaluated during project duration.
Construction	Two layers of corrosion-resistant casing required and set through lowermost USDW. Cement compatible with subsurface geology.
Operation	Injection pressures may not initiate or propagate fractures into the confining zone or cause fluid movement into USDWs. Quarterly reporting on injection, injected fluids and monitoring of USDWs within the AoR. Must report changes to facility, progress on compliance schedule, losing of mechanical integrity, or noncompliance with permit conditions. Permit valid for 10 years.
Mechanical Integrity Test (MIT)	Continuous internal integrity monitoring and annual external integrity testing.
Monitoring	Analyze injectant. Continuous temperature and pressure monitoring in the target formation. Plume tracking required.
Closure	50 day notice and flush well. Must be plugged to prevent injectant from contaminating USDWs.
Proof of Containment and Post-Closure Care	Post-closure site care for 50 years or until proof of non-endangerment to USDWs demonstrated. (No-migration petition demonstration; fluids remain in injection zone for 10 000 years).
Financial Responsibility	Periodically update the cost estimate for well plugging, post injection site care and site closure, and remediation to account for any amendments to the area of review and corrective action plan. EPA is also proposing that the owner or operator submit an adjusted cost estimate to the Director if the original demonstration is no longer adequate to cover the cost of the injection well plugging, post-injection site care, and site closure.

Table 8.15 Mandatory technical requirements for CO2 injection well (NETL, 2009)

8.4.3 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).

8.5 Macedonia Basin (Greece)

The Mesohellenic Basin is in very low maturity stage and currently under technical investigation to increase understanding of the area and its commerciality potential. The current investigation is mostly focused in geological mapping and laboratory investigation to provide modelling conceptualisation of the area to see its behaviour while reducing its potential operational risk from CO2 leakage. The

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geological model will be greatly enhanced through the re-processing of large-scale vintage seismic data which is currently being analysed from HEREMA (Figure 26).

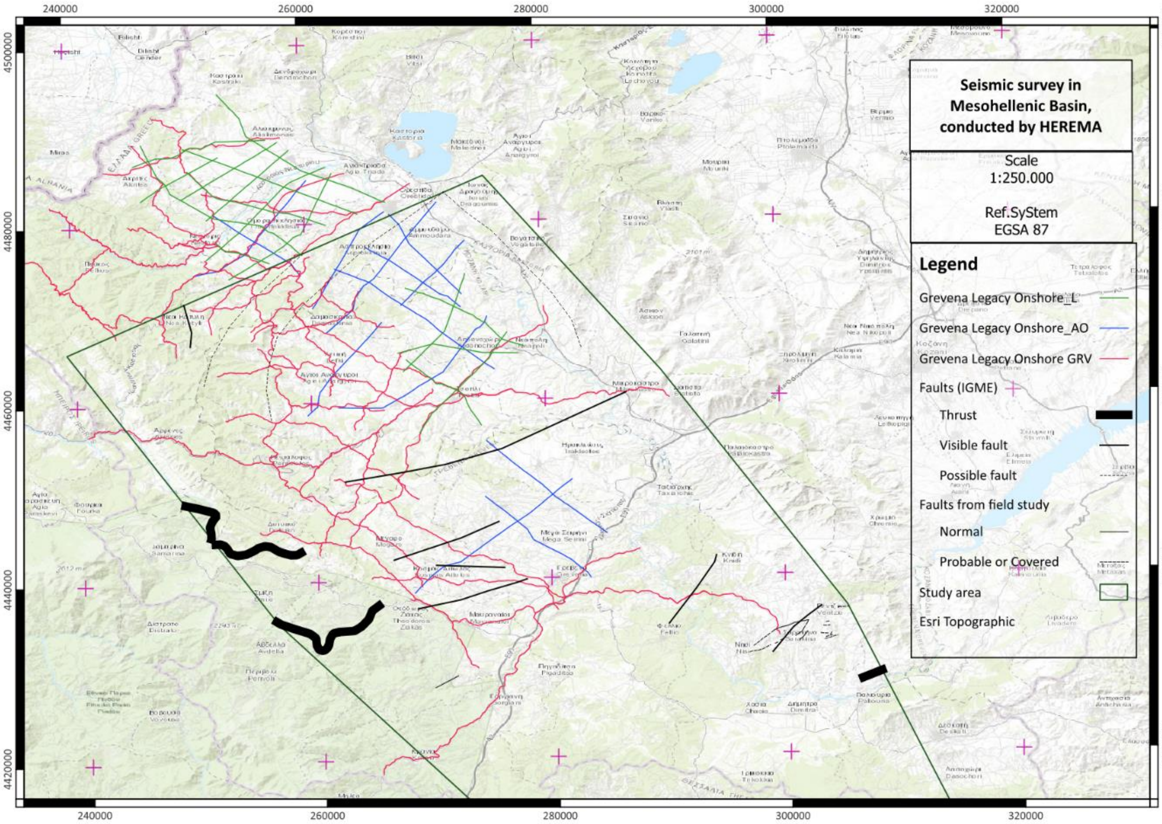

Figure 26 Location of vintage seismic lines in the Mesohellenic Basin

Until the latest updates, there are no dedicated CO_2 reception or injection facilities in West Macedonia. The region of Mesohellenic Basin is still at an early stage of planning and evaluation, while most of efforts are focussing on geological characterisation and scenario development for future deployment. The proposed injection sites are located in the Mesohellenic Trough, approximately 40–50 km from the main emission source at Ptolemaida V (Koukouzas et al., 2023). The two main formations identified for injection are described in Table 8.16:

Characteristics	Pentalofos Formation	Eptachori Formation
Depth	~3500 m	~5000 m
Thickness	~2500 m	~1100 m
Estimated Capacity	1.02–1.277 Gt CO_2	0.13–0.17 Gt CO_2
Lithology	Conglomerates, turbiditic sandstones, and shales	Marine sandstones, turbiditic shales, pebbly conglomerates

Table 8.16 Characteristics of storage geological formations of the Mesohellenic Basin

Pentalofos and Eptachori Formations are classified as Tier 1 resources under the USDOE methodology as they are conceptually assessed. However, they require substantial additional data and field verification prior to the beginning of commercial injection processes. In Pentalofos Formation, high injection volumes will be noticed between 2030 and 2033, while they will gradually decline thereafter.

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In Eptachori Formation, high initial injection will be up to 2035. From 2040 to 2050, the injection rate will be stable at a rate of 0.1 Mt CO_2/year (Coussy, P., 2021).

Topography between the Ptolemaida area and the Mesohellenic Basin is mountainous, and thus the pipeline construction and the pressure maintenance are more complex and expensive. The reuse of existing infrastructure is not feasible in the case of West Macedonia. While the Trans Andriatic Pipeline (TAP) is nearby, it is not suitable for CO_2 transport as it is designed for natural gas. Future injection wells require custom-designs, which are currently conceptual, to fit the geological and pressure conditions of each formation (Carneiro, J.M. and Mesquita, P., 2020).

Although Mesohellenic Basin, and thus West Macedonia does not yet have operational CO_2 reception and injection infrastructure, detailed scenarios have been described for the Pentalofos and Eptachori formations. The Mesohellenic Basin holds strong potential for CO_2 storage but proceeding from Tier 1 to operational status require additional geological studies, pilot injection testing, and investment in site-specific infrastructure development.

9. Conclusions

1. **Integrated CCS Chain Design**
   The document successfully outlines the technical and economic framework for implementing full-chain Carbon Capture and Storage (CCS) systems—from source to injection—across multiple European regions. It emphasizes the importance of tailoring solutions to regional conditions while maintaining a harmonized methodology.

2. **Technology Readiness and Flexibility**
   A wide range of CO_2 capture technologies are available, with chemical absorption (especially MEA-based systems) being the most mature and widely applicable. However, the document also highlights the potential of emerging technologies (e.g., membranes, cryogenics, DAC) for future deployment, depending on site-specific constraints and industrial profiles.

3. **CO_2 Stream Quality and Safety Standards**
   The report stresses the need for strict control of CO_2 stream composition to ensure safe transport and storage. It aligns with ISO-27913 and EU CCS Directive requirements, recommending high-purity CO_2 streams with minimal impurities to avoid corrosion, hydrate formation, and environmental risks.

4. **Transport Strategy Must Be Phase-Appropriate**
   - Pilot phases benefit from flexible, lower-cost transport options (e.g., truck, rail, ship).
   - Commercial phases require scalable, continuous transport systems—primarily pipelines—to ensure cost-effectiveness and operational reliability over decades.

5. **Infrastructure Design Is Critical for Long-Term Viability**. The design of reception and injection facilities must consider:
   - Corrosion-resistant materials.
   - Multistage compression systems.
   - Advanced monitoring and safety systems (e.g., fiber optics, DAS/DTS, SCADA).

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- Modular and expandable layouts to accommodate future scale-up.

6. **Cost Estimates Provide Realistic Benchmarks**. The document provides Class V cost estimates for both pilot and commercial phases, offering a realistic baseline for investment planning. While pilot phases are more expensive per ton due to limited scale, commercial phases benefit from economies of scale, especially in transport and injection infrastructure.

7. **Adaptability and Iterative Design Are Essential**.
   The deliverable acknowledges that all designs are preliminary and must evolve based on:
   - Results from ongoing geological, engineering, and economic studies.
   - Stakeholder engagement and regulatory developments.
   - Lessons learned from pilot operations.

8. **Strategic Value of Regional CCS Hubs.** The study reinforces the strategic importance of developing regional CCS hubs that can serve multiple emitters and storage sites. This approach enhances cost-efficiency, infrastructure utilization, and cross-border cooperation, particularly in regions like West Macedonia and Lusitania.

9. **Regulatory and Permitting Frameworks Need Strengthening**. Several regions still lack mature regulatory environments for CCS deployment. The document calls for clearer permitting procedures, monitoring protocols, and liability frameworks to support full-scale implementation.

10. **PilotSTRATEGY as a Foundation for Future CCS Deployment**.
    Deliverable D4.5 lays a solid foundation for advancing from conceptual design to implementation. It provides the technical, economic, and regulatory insights needed to de-risk investment decisions and accelerate the deployment of CCS as a key tool for achieving climate neutrality in Europe.

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