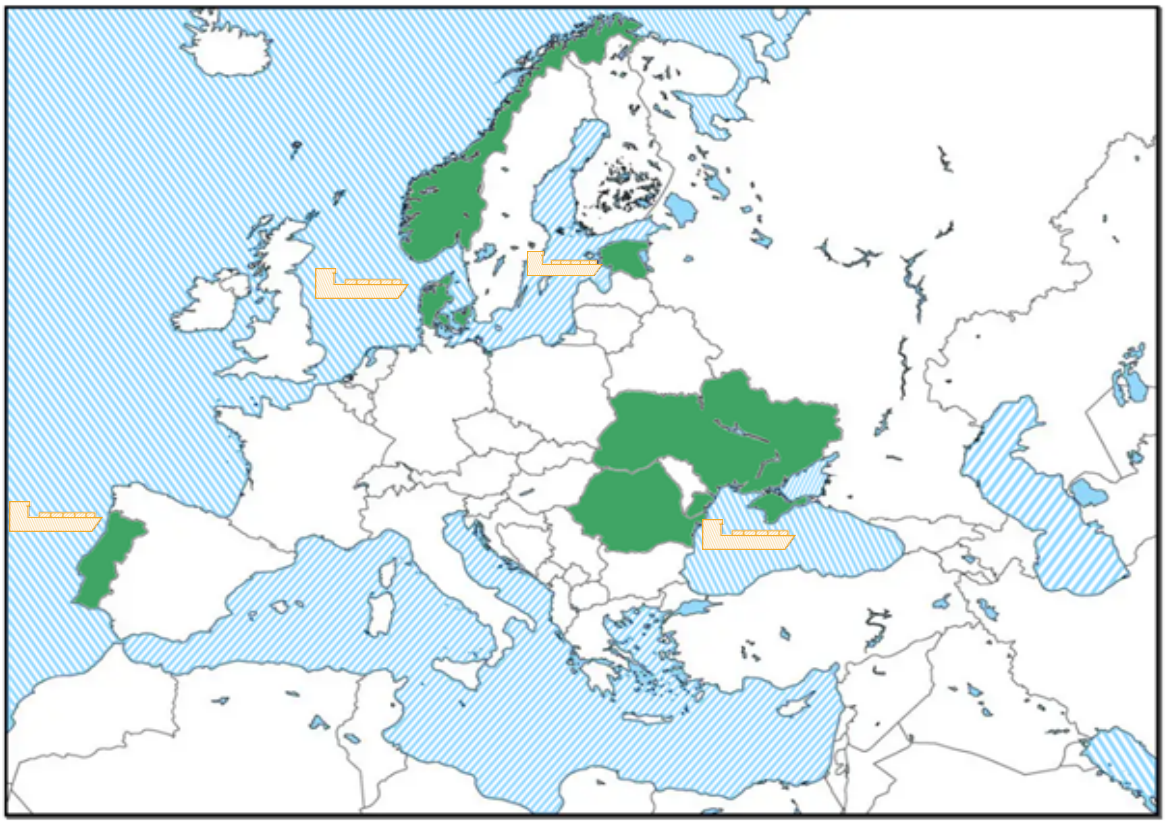
CO_2 Transport and Storage directly from a ship: flexible and cost-effective solutions for European offshore storage

Deliverable 3.2

Techno-economic drivers and challenges for direct ship injection including replicability analysis



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Executive Summary

This deliverable assesses the techno-economic drivers, barriers and replicability potential of Direct Ship Injection (DSI) as a CO_2 transport and offshore storage solution in Europe. DSI uses a CO_2 carrier equipped to connect directly to a subsea injection system, enabling captured CO_2 to be transported from port facilities and injected into an offshore geological reservoir without requiring a permanent offshore injection platform or a dedicated offshore pipeline. The concept is particularly relevant in early CCS deployment phases, when capture volumes are dispersed, transport networks are immature, and the investment case for large-scale pipeline infrastructure has not yet been established.

The project focuses on the Atlantic Coast of Portugal: the Baltic Sea, the Black Sea and the North Sea. Across these regions, DSI is found to offer three principal advantages, flexibility in connecting geographically dispersed emitters, shorter time-to-market relative to extensive pipeline systems, and lower up-front infrastructure requirements at the storage site. It can therefore provide a practical transitional solution, allowing early emitters and port clusters to access offshore storage while larger shared CCS networks are being developed. DSI can also support progressive scaling, as additional vessels, emitters and storage sites may be incorporated as CO_2 volumes grow.

The regional assessments demonstrate that the value proposition for DSI depends strongly on local conditions. In Portugal, DSI can connect the Sines and Setúbal clusters to the offshore storage structure near Figueira da Foz. In the Baltic Sea, it can potentially link emitters across Estonia, Latvia and Lithuania to offshore storage, although regulatory development, cross-border arrangements and storage-site maturation are critical prerequisites. In the Black Sea, DSI provides a flexible route for emerging CCS clusters in Romania and Ukraine, where port infrastructure and offshore storage prospects exist but market maturity, geological characterisation and regulatory certainty remain limited. In the North Sea, DSI can exploit established offshore operational capability and accommodate dispersed European CO_2 volumes before dedicated high-capacity infrastructure becomes economically justified.

The main barriers to deployment are regulatory, operational and commercial, but also include the remaining maturity gap of the platform-free DSI configuration. Although Project Greensand provides a commercial-scale reference for ship-based offshore CO_2 injection that has close similarities with DSI, direct connection from the vessel to a subsea well without an offshore platform still requires demonstration. Several regions also lack clear rules for ship-based CO_2 transport, direct ship-to-well injection, cross-border transport, permitting, monitoring and long-term liability. Stakeholder engagement is equally important, particularly where operations may interact with fisheries, shipping, tourism, offshore wind, protected areas or other marine activities.

Finally, chapter 4 provides a complementary Mediterranean replicability assessment for selected sources, port hubs and storage sites in Spain, France, Italy, Greece, Morocco and Egypt. Conventional shipping, DSI and pipeline configurations are compared for the offshore transport segment at network level. Under the assumptions adopted, DSI is not selected in the global minimum-cost configuration but appears in several near-optimal configurations, particularly for the France–Ravenna and Greece–Ravenna connections. These results identify routes where DSI may justify further assessment but do not constitute a detailed techno-economic feasibility assessment of its deployment in the Mediterranean.

DSI should be regarded as a complementary CCS transport option rather than a universal replacement for pipeline or conventional ship. It may be relevant for long distance and most attractive for early-

phase deployment, low-to-medium volumes, dispersed coastal emitters and storage sites where permanent offshore infrastructure would impose high initial costs. At larger, stable and concentrated volumes, pipelines may become more cost-effective; however, DSI can continue to serve remote sources, smaller emitters and new storage locations.

Overall, DSI can accelerate European offshore CCS deployment by enabling phased, flexible and lower-infrastructure transport-and-storage chains. Its practical application will depend on demonstration of the platform-free vessel-to-well configuration, confirmation of storage performance under batch injection, clear permitting pathways, adequate port and offshore infrastructure, defined commercial arrangements and early engagement with regulators and marine stakeholders.

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Abbreviations and Units

Abbreviations

ALG	-	Algeciras
BAR	-	Barcelona
BECCS	-	Bioenergy with Carbon Capture and Storage
BSR	-	Baltic Sea Region
CAPEX	-	Capital Expenditure
CBAM	-	Carbon Border Adjustment Mechanism
CCS	-	CO_2 Capture and Storage
CCU	-	Carbon Capture and Utilization
CCUS	-	CO2 Capture, Utilization and Storage
CO_2	-	Carbon Dioxide
DP	-	Dynamic Positioning
DR	-	Discount Rate
DSI	-	Direct Ship Injection
EC	-	European Commission
EIA	-	Environmental Impact Assessment
EN-H2	-	National Hydrogen Strategy
E-PRTR	-	European Pollutant Release and Transfer Register
ETS	-	Emission Trading System
EU	-	European Union
EU ETS	-	European Union Emission Trading System
FEED	-	Front-End Engineering and Design
GEN	-	Genoa
GHG	-	Greenhouse Gas
GIA	-	Gioia Tauro
HELCOM	-	Baltic Marine Environment Protection Commission
IR	-	Inflation Rates
LCA	-	Life Cycle Assessment
LULUCF	-	Land Use, Land-Use Change, and Forestry
MPA	-	Marine Protected Area
MRV	-	Monitoring, Reporting and Verification
NAMRMPSG	-	National Regulatory Authority in the Mining, Petroleum and Geological Storage of Carbon Dioxide
NCCMA	-	National Climate Change Management Agenda
NDC	-	Nationally Determined Contribution
NECP	-	National Energy and Climate Plan
NGO	-	Non-Governmental Organization
nPV	-	Normalized Present Value
NZIA	-	Net Zero Industry Act
OPEX	-	Operating Expenditure
OSPAR	-	Convention for the Protection of the Marine Environment of the North-East Atlantic
PCI	-	Projects of Common Interests
PI	-	Pipeline
PIPE	-	Pipeline scenario for emitter-hub-storage transport
PNEC 2030	-	National Energy and Climate Plan 2030
RNC 2050	-	Carbon Neutrality Roadmap 2050
RSS	-	Resonance Spectral Sounding
SHIP	-	Conventional Ship
TEA	-	Techno-economic Analysis

UNFCCC	-	United Nations Framework Convention on Climate Change
VAL	-	Valencia
k	-	k-split value, mass distribution ration between reservoirs
u	-	Umbilical cord cost

Units

%	-	Percentage
°C	-	Degree Celsius
km	-	kilometre
kt	-	kiloton
kt/yr	-	kiloton per year
m	-	meters
Mt	-	Million tonnes
Mt/yr	-	Million tonnes per year
NOK/t	-	Norwegian Krone per ton
bar	-	SI unit of pressure
t	-	tonne

1 Introduction

Carbon capture and storage is expected to play an important role in decarbonising industrial sectors for which direct electrification, fuel switching or process changes alone cannot eliminate emissions. However, the deployment of CCS depends on the coordinated development of capture facilities, transport systems, ports, offshore infrastructure, geological storage sites, regulatory frameworks, social acceptance and commercial arrangements. The transport-and-storage segment is particularly challenging where emitters are dispersed, captured volumes are initially limited, storage sites are offshore, or cross-border infrastructure would be required.

Addressing these challenges, a Direct Ship Injection (DSI) concept enables efficient transportation and injection of CO_2 from shore to offshore site directly. CO_2 is stored in onboard storage tanks that are specifically designed for required conditions. In the conventional ship designs, where CO_2 is loaded in the CO_2 carriers, an offshore platform/floating installation is needed to facilitate conditioning and injection at offshore site. DSI eliminates the requirement of offshore platforms and helps decreasing visual impacts of such permanent infrastructure in the areas relying on coastal and marine tourism, and reduces constraints to other marine activities, such as fisheries[1]. CO_2 is loaded at port into specially designed tanks and transported to the offshore storage site (see Figure 1). The solution is designed for both shallow and deep waters, for use with dynamic positioning or mooring system, making it adaptable to varying sea conditions.

CO_2 is transported in liquid phase at medium pressure (15 bar and -29°C). With the increasing demand to transport CO_2, studies consider transport capacity of up to 100,000 t per vessel[2]. DSI vessel is equipped with onboard CO_2 conditioning unit to match the required injection parameters, as shown in Figure 2. To achieve the required parameters, CO_2 is first pressurized using specially designed pumps to the required pressure. Pressurized CO_2 is then heated using sea water and/or by an electric heater. The process of first pressurizing and followed by heating minimizes the energy requirements while simultaneously preventing phase transition during the conditioning. The vessel is also equipped with an offloading connection system to connect the injection system with the offloading hose and a control cable that can control the valves in the subsea wells.

The concept aims to enhance CCUS adoption by connecting smaller emitters and regions lacking storage capacity to enable faster deployment. Overall, the objective of the technology is to provide a low-cost transportation solution with flexible and scalable capacity, adoptable to market needs.

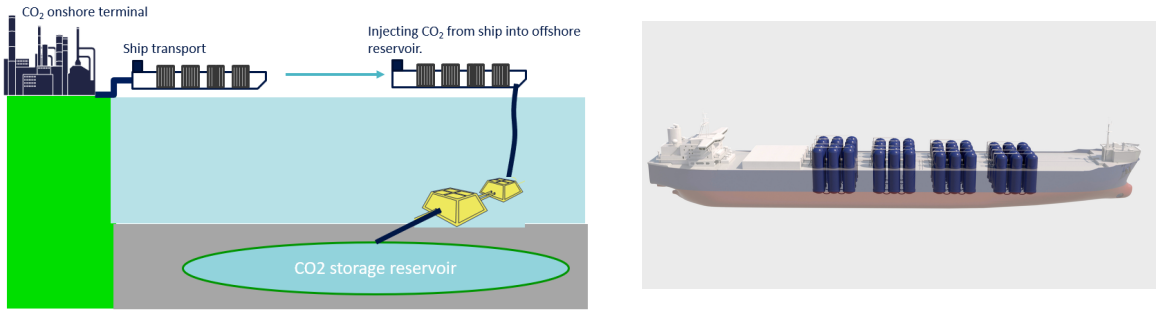


Figure 1. Direct Ship Injection concept by NEMO Maritime showing offshore CO_2 transport and injection chain along with ship design.

[1] CO2 Transport and Storage directly from a ship: flexible and cost-effective solutions for European offshore storage (CTS). - Norce

[2] Danish Energy Agency. (2024). *Technology data - Carbon capture, transport and storage* (Version 0003). Danish Energy Agency.

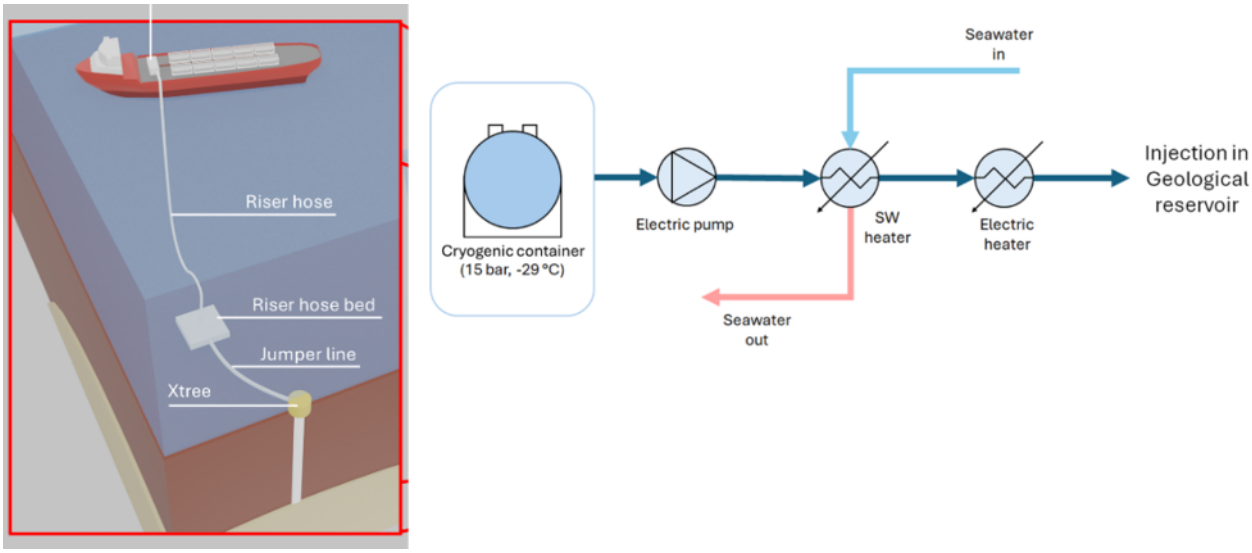


Figure 2. Onboard CO_2 conditioning system schematic diagram to match injection requirements of CO_2.

1.1 Objective and structure of the report

This deliverable examines the techno-economic, regulatory, environmental, logistical and stakeholder conditions affecting DSI deployment in four European regions. These regions are the Atlantic Coast of Portugal (Portugal), the Baltic Sea (Estonia-Latvia-Lithuania), the Black Sea (Ukraine) and the North Sea (Norway). The assessment identifies drivers and barriers, evaluates their regional relevance and proposes recommendations to improve the deployment and replicability of DSI.

The report examines the potential for DSI in the selected European regions. The focus is on regulatory and legal frameworks, transboundary cooperation (where required), environmental assessment requirements, market assessment and stakeholder collaboration. The final assessment summarises the key challenges and opportunities for DSI deployment identified in each region.

Chapter 3.4 extends the analysis to the Mediterranean as an exploratory replicability exercise, to evaluate DSI feasibility in the area, comparing conventional shipping, DSI and pipelines through an optimisation-based assessment focused on the offshore transport segment, in order to identify the network conditions under which DSI may be economically competitive. Although the analysis provides useful comparative evidence, it is not intended as a detailed techno-economic feasibility assessment of DSI deployment in the Mediterranean, but rather to provide indications of where such techno-economic feasibility should be addressed in later studies. The primary purpose of this deliverable remains to identify the drivers, barriers and enabling conditions for practical DSI deployment across the four core regional case studies.

The report is organised into five chapters. Chapter 1 introduces the objectives and rationale of the deliverable and includes a concise description of the DSI concept. Chapter 2 presents the methodological framework used to identify and compare the drivers, opportunities, barriers and challenges affecting DSI deployment. Chapter 3 provides the region-specific assessments for the Atlantic Coast of Portugal, the Baltic Sea, the Black Sea and the North Sea, covering the regional context, principal drivers and opportunities, main barriers and risks, and recommended actions. Chapter 4 extends the assessment to the Mediterranean through an exploratory replicability exercise covering selected emitters, ports and offshore storage sites. Finally, Chapter 5 identifies the main cross-regional patterns, distinguishes the conditions specific to each region, discusses the implications of the Mediterranean assessment and presents the overall conclusions.

2 Methodology

2.1 Qualitative assessment of drivers and challenges

The methodology follows a **qualitative assessment** to identify barriers and challenges to implement DSI as a credible transport-and-storage solution in each of the four regions, which factors most strongly influence its feasibility, and what measures are needed to enable replication across different European offshore CCS contexts.

A common questionnaire and classification framework were applied to the four target regions and completed by the participating local teams, to ensure that the assessment was systematic and comparable. The framework covers seven categories:

1. Regulatory environment
2. Environmental aspects
3. Socio-economic impacts
4. Technical feasibility
5. Infrastructure and logistics
6. Maturity and time-to-market
7. Site-specific geological factors.

Each category is broken down into guiding questions designed to capture the relevant technical, commercial, legal, environmental and societal conditions for DSI deployment in a specific region (see References).

for details). Each local team identifies the current barriers and opportunities through these guiding questions for the DSI deployment in each region. The assessment requires local teams to consider the barriers and challenges faced by DSI relative to pipeline and conventional ship-based transport configurations where such alternatives are applicable. This is followed by region specific recommendations that are needed in order to implement the DSI solution.

Answers to each guiding question are summarized at two levels:

Regional Status: a direct reply from local teams about the local status on the specific question, where “Yes” or “No” if there is definite answer and, with “Undefined” if there is not enough information available to conclude any outcome.

Regional relevance: an assessment from local teams about the relevance to the DSI deployment based on the regional response on a colour coded scale:

- green represents no relevance;
- lime-green shows minor relevance;
- yellow means important relevance;
- and red represents critical relevance in the colour scale.

Where a single relevance scale is not possible to award due to uncertainty between two scores or is in an intermediate stage, dual colour is used to represent its possible upper and lower relevance colours. The status and relevance matrices are represented in the specific regional discussion in Chapter 3.

Based on the regional relevance assigned to each guiding question, an overall relevance score is calculated for each of the seven categories. This score represents the category’s relevance in each region and supports the identification of priority categories. Scores are based on 24 questions, each

rated from 0 to 3 where, 0 = none, 1 = minor, 2 = important, and 3 = critical. The category score is calculated as the average of the underlying regional status questions.

When a question has an uncertain score range, such as 1–2, lower- and upper-bound category scores are calculated using the respective limits. These bounds are rounded to the nearest whole number to produce a plausible relevance range for each category. The resulting ranges are plotted by region in Chapter 3.

Although the same assessment framework was applied to all four regions, the relevance and implications of the identified drivers, opportunities, barriers and challenges vary according to the regional conditions and the assessment of the local teams. Cross-regional patterns and regional differences are therefore derived from the completed regional assessments and discussed in the final synthesis.

2.2 Mediterranean replicability assessment

Chapter 4 applies a quantitative approach to assess the replicability of DSI solution in a Mediterranean network. Conventional shipping, DSI and pipelines are compared for the offshore transport segment connecting selected port hubs in Spain, France, Italy, Greece, Morocco and Egypt to the Ebro, Ravenna and Prinos storage options. The assessment focuses only on the offshore transport segment, while capture costs, onshore transport to the ports, well drilling and infrastructure common to all transport configurations are excluded.

The exercise is exploratory and is intended to identify connections where DSI may justify further assessment. It should not be interpreted as a detailed feasibility assessment of DSI deployment in the Mediterranean.

The assessment combines the screening of emitters and port hubs with a network optimisation model. Industrial CO_2 volumes are based on CCUS ZEN and facility-level emissions databases and are adjusted using sector-specific reduction factors and a minimum source threshold. For each hub-to-storage connection, the model evaluates the available transport-mode combinations, and optimises the allocation of CO_2 between storage sites where more than one option is available. Spanish and Italian port selection require additional screening therefore, the optimisation is repeated for all the combinations of Spanish and Italian ports. Infrastructure sizing and cost relationships follow D3.1. The different configurations are compared using lifetime discounted cost and normalised present value.

The detailed screening assumptions, model formulation, financial parameters, optimisation procedure and equations are presented in Annex B.

3 Regional barriers, opportunities and recommendations

This section summarises the drivers, barriers, and opportunities for DSI relative to alternative pipeline and conventional ship-based transport configurations (where applicable) for all the regions, following the classification framework.

3.1 Baltic Sea

3.1.1 Regional Context

Policy and decarbonization framework

The Baltic scenario includes CO_2 emissions from three Baltic States (Estonia, Latvia and Lithuania) with CO_2 storage in the E6 structure offshore Latvia. All three countries have plans to become carbon neutral by 2050 with varying intermediate targets. In Estonia's Climate Law (Climate Resilient Economy Act) draft, 63% of total GHG emissions reduction by 2030, 71% by 2035, 80% by 2040 compared to 1990[3] is planned. Latvia and Lithuania both have a higher target of 85% by 2040 whereas, comparatively lower target of 65% and 70% by 2030 for Latvia and Lithuania[4,5] respectively compared to 1990. Despite the Baltic countries' ambitious climate plans, their NECPs do not include concrete implementation plans for CCS.

From the Baltic countries, Latvia has the best geological conditions for CO_2 storage (low reservoir temperatures, which permit the liquid subcritical CO_2 phase in onshore structures), and is the only Baltic State with high potential to unlock CO_2 storage capacity by 2030. According to the applicable laws, the transport of CO_2 is permitted in all Baltic Sea Region countries.

As reported in D2.1, the Contracting Parties to the Baltic Marine Environment Protection Commission (HELCOM) who are included in the CETP CTS project scenarios are Denmark, Estonia, Latvia and Lithuania (and the EU). The regulations on CO_2 storage are not yet included in HELCOM, meaning that CO_2 storage is prohibited in the Baltic Sea Area. However, in 2025, HELCOM decided to establish a Task Force to conduct an environmental analysis concerning CO_2 storage beneath the Baltic Sea, as part of the ongoing dialogue regarding the Helsinki Convention. The CCS Taskforce on environmental analysis started its work in August 2025 and will finalise the planned reports in 2026. On 2nd September 2025, HELCOM published a Call for Tender: legal analysis of CCS in accordance with the Helsinki Convention[6]. The draft versions of the reports are now being discussed by HELCOM parties; the final versions will be ready by the end of 2026.

CO_2 emitters and capture

As reported in D2.1 and D3.1, the Baltic scenario includes 16 plants across 4 clusters in three countries. Where three clusters include 6 sub-clusters (Table 1). Due to the lack of publicly available sources reporting biogenic CO_2 emissions in Latvia and Lithuania, the scenarios report biogenic emissions only for the Estonian sources. Only the total emissions reported in the EU ETS were known for Latvian and Lithuanian sources, and they were included in the scenario. However, Schwenk Latvia cement factory has been using energy from waste for the last decade, and only their process emissions should be fossil. Two Lithuanian waste-to-energy plants also produce a significant share of biogenic emissions.

[3] https://kliimaministeerium.ee/eesti-kliimaseadus
[4] Latvia's climate action strategy
[5] Lithuania's climate action strategy
[6] https://helcom.fi/call-for-tender-legal-analysis-of-ccs-in-accordance-with-the-helsinki-convention/

Exact amounts of bio-CO_2 versus fossil emissions they will need to report publicly in future periods, according to amendments in the EU ETS proposed by the EC in July 2026[7].

Table 1. List of emitters considered in the Baltic scenario and CO_2 emissions available for capture.

ID	EU ETS ID	Country	Emitter Name	Cluster	Sector	CO_2 emissions 2023, Mt/yr
1	KKL-324417	Estonia	Auvere PP	Estonian, Ida-Viru	Power	0.94
2	KKL-176540	Estonia	Auvere SOP	Estonian, Ida-Viru	Shale Oil Plant	0.98
3	KKL-300389	Estonia	VKG SOP	Estonian, Ida-Viru	Shale Oil Plant	0.72
4	L-KKL-IV-204118	Estonia	VKG Energia North TP	Estonian, Ida-Viru	Power	0.62
5	L-KKL-IV-171223	Estonia	Kiviõli Chemical P	Estonian, Ida-Viru	Shale Oil Plant	0.23
6	L-KKL-HA-217188	Estonia	Horizon Paper Factory	Estonian, Tallinn-Harju	Paper	0.125
7	L-KKL-HA-162843	Estonia	Utilitas Tallinn PP	Estonian, Tallinn-Harju	Power	0.16
8	L-KKL-HA-222658	Estonia	Iru WtEP	Estonian, Tallinn-Harju	WtE	0.15
9	KU20SG0008	Latvia	Schwenk Latvia	Latvian-Lith., Latvian	Cement	0.74
10	LV-RIT-R-II-SEG-07	Latvia	Latvenergo Tec-2	Latvian	Power	0.55
11	LV-RIT-R-II-SEG-06	Latvia	Latvenergo Tec-1	Latvian	Power	0.15
12	T-KL1-3-2014	Lithuania	Gren Klaipėda WtEP	Latvian-Lith., West Lith.	WtE	0.1
13	T-S-4-6-2015	Lithuania	Orlen Lietuva	Latvian-Lith., North Lith.	Refineries	1.65
14	T-S-1-1-2014	Lithuania	Akmenės Cement	Latvian-Lith., North Lith.	Cement	0.78
15	T-K-4-24-2019	Lithuania	UAB Kauno WtEP	Latvian-Lith., Kaunas	WtE	0.12
16	2-15	Lithuania	Achema	Latvian-Lith., Kaunas	Chemical	1.36
					Totals	**9.375**

CO_2 storage site

The Baltic scenario relies on the E6 offshore geological structure in the Latvian sector of the Baltic Sea as the primary CO_2 storage site (Figure 3). The Cambrian Wuliuan Deimena Formation sandstone reservoir in the E6 structure is located at depths exceeding 850 m. A 53-meter-thick sandstone reservoir is covered by 46-meter-thick shales as the primary cap rock of the Lower Ordovician Zebre Formation, and by Ordovician and Silurian secondary clayey carbonate cap rocks about 300 m thick. The presence of a 10 m-thick oil layer in the Upper Ordovician Saldus Formation provides additional evidence of the E6 structure's excellent sealing properties.

[7] EC, (2026). Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 2003/87/EC and Decision (EU) 2015/1814 as regards driving competitiveness and cost-effective decarbonisation. EUR-Lex - 52026PC0616 - EN - EUR-Lex

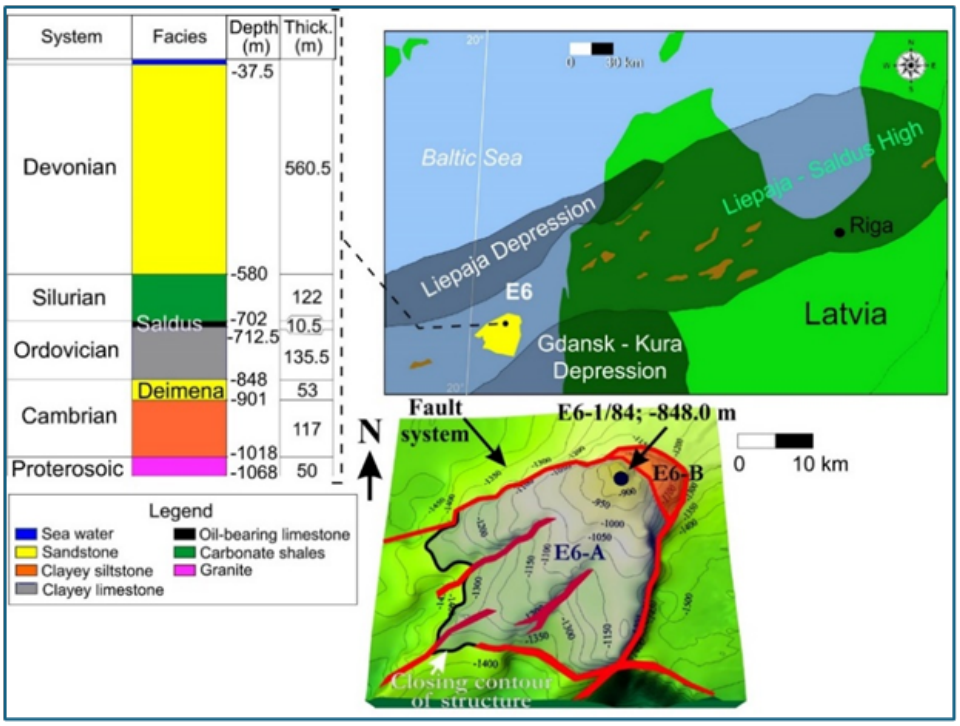


Figure 3. The E6 Latvian offshore underground geological structure, prospective for CO_2 storage in the Cambrian aquifer (yellow), with the location of the well E6-1/84 and lithological cross-section, and the 3D geological model of the top of the Cambrian Deimena Formation of the E6 structure. Location of smaller compartment E6-B is indicated by red transparent colour[8,9].

The prospective CGS reservoir of the Cambrian Wuliuan Deimena Formation sandstone (848–901 m depth at well E6-1/84) in the E6 structure was assessed as the largest storage site among those studied in the Baltic Region. The conservative and optimistic average CO_2 storage capacity of the Deimena Formation sandstone reservoir in part A of the E-6 (see Figure 3) structure was estimated at 146-365 million tonnes (Mt). The CO_2 storage capacity of the total Cambrian reservoir (parts A and B) is 152-377 Mt[10]. The estimated optimistic storage capacity of approximately 365 Mt CO_2 was considered for the Baltic Scenario.

Transport configuration description

CO_2 is transported from industrial emitters to four regional ports through a network of pipelines with a total length of approximately 730 km (Figure 4. , see D2.1 and D3.1 for further details). The pipeline distance to ports ranges from 7.5 km (from Latvenergo Tec-1 to Riga Port) to 230 km (from Achema in Kaunas to Klaipeda Port). CO_2 accumulated at these ports are then transported to E6 Latvian offshore storage site via ships with the following route: (1) from the port of Sillamäe to the E6 (751 km), (2) from the port of Muuga to the E6 (575 km), (3) from the port of Riga to the E6 (402 km), (4) from the port of Klaipėda to the E6 (90.5 km).

[8] Shogenov K, Shogenova A, Gei D, Forlin E. Synergy of CO2 storage and oil recovery in different geological formations: case study in the Baltic Sea. Elsevier. Energy Procedia 2017; 114:7047–7054. https://doi.org/10.1016/j.egypro.2017.03.1846

[9] Shogenov, K., & Shogenova, A. (2021). Innovative synergy CCUS and renewable energy project offshore Baltic using CO_2 emissions from the cement industry. In *15th International Conference on Greenhouse Gas Control Technologies (GHGT-15)* (pp. 1–11). Elsevier. https://doi.org/10.2139/ssrn.3812387

[10] Shogenov K, Shogenova A, Vizika-Kavvadias O. Potential structures for CO_2 geological storage in the Baltic Sea: case study offshore Latvia. Bulletin of the Geological Society of Finland 2013; 85(1): 65-81.

In Lithuania, KN Energies, located in Klaipeda Port, has already signed a FEED (front-end engineering and design) contract with Aker Solutions for the construction of a multimodal LCO_2 import/export terminal in the Port of Klaipeda, as part of the EU PCI - CCS Baltic Consortium. The CO_2 terminal is expected to begin commercial operations in 2030[11].



Figure 4. Baltic Offshore Cross-Border Scenario. The transparent yellow circles represent the clusters and sub-clusters. Estonian Cluster: (1) Ida-Viru (northeastern) sub-cluster leading to Sillamäe Port, (2) Tallinn-Harju sub-cluster connected to Muuga Port. Latvian Cluster: (3) associated with the Riga Port. Latvian-Lithuanian Cluster linked to Klaipeda Port: (4)

3.1.2 Main DSI drivers and opportunities

Regional response of categorized guiding questions for qualitative assessment for the Baltic Sea region is represented in the Figure 5. Figure records the regional response to the questions as well as the colour code representing relevance of each question for the deployment of DSI in the region.

[11] KN Energies signs Grant Agreement with the European Commission - CCS Baltic Consortium project

Guiding questions	Baltic Sea	
	Regional status	Regional relevance
Regulatory environment		
Regulations for CO2 transport by ship exists?	No	
Are ship permits faster than offshore pipelines?	Yes	
Are absence of pipeline regulations an opportunity?	Yes	
Environmental aspects		
Are noise impacts from ships an issue?	Undefined	
Are pipelines and platforms a concern?	Yes	
Can potential CO2 leaks compromise habitats?	No	
Is direct injection an environmental concern?	No	
Socio-economic impacts		
Are the visual impacts of platforms a concern?	No	
Are there possible conflicts with stakeholders?	Undefined	
Does direct injection favour job creation?	No	
Is there higher social acceptance for reversible solutions?	Undefined	
Technical feasibility		
Are the maritime conditions challenging?	Undefined	
Are there long non-operational periods due to weather?	Undefined	
Is there continuous supply of CO2	Yes	
Is continuous injection favoured by injectivity?	Yes	
Infrastructure & Logistics		
Do CO2 sources favour transport to a port?	Yes	
Are many small-scale CO2 sources identified?	Yes	
Is the platform technically justified for the expected capacity?	Yes	
Maturity & time-to-market		
Is rapid deployment needed?	Yes	
Is the pilot phase expected?	Yes	
Does direct injection accelerate deployment?	Yes	
Site-specific geological factors		
Is the reservoir injectivity suitable for intermittent injection?	Undefined	
Will initially only 1–2 wells be available?	Yes	
Is the storage site remote (e.g., deep water)?	No	

Figure 5. Regional status of guiding questions response along with their relevance for Baltic Sea region (Colour code - Green: No relevance, Lime-green: Minor relevance, Yellow: Important relevance, Red: Critical relevance, double colour: possible lower relevance (left) with possible upper relevance (right)).

Figure 6 shows the cumulative relevance of each category for the Baltic Scenario across all classifications based on the scoring awarded in Figure 5. Solid bars show the baseline relevance scores, while hollow bars stacked on top reflect additional potential relevance where scoring ranges apply, capturing uncertainty between two scoring levels.

Regulatory environment, maturity, and time-to-market are the highest-scoring categories, showing critical relevance for DSI. This reflects the critical importance of both regional and national regulations in the Baltic Region and the rapid implementation of DSI technology in the Baltic to start as soon as possible, before all planned Baltic PCI will transport their CO_2 emissions to more distant storage sites (for example, in the North Sea, or onshore Denmark). Environmental aspects, technical feasibility, and site-specific geological conditions, all show important relevance, underscoring their importance, yet remain manageable with adequate permitting, exploration, monitoring, operational planning, and

industrial engagement. Socio-economic impacts, infrastructure, and logistics received minor scores, given the extensive technical experience in the Baltic Sea with technical and shipping projects, the proximity to the shore, and shallow waters.

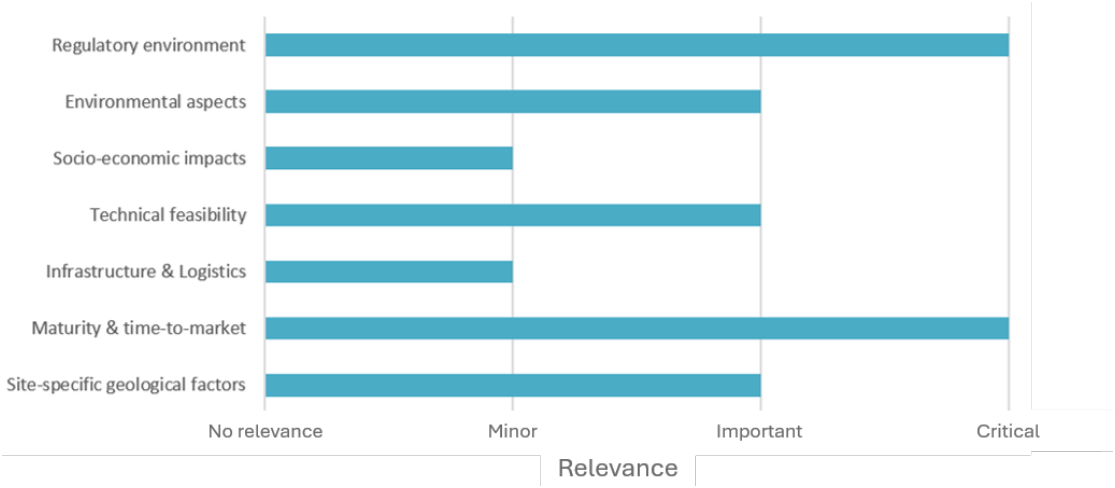


Figure 6. Cumulative relevance of each guiding category related to DSI implementation in the Baltic Sea region.

The main drivers for DSI in the Baltic Sea are:

- **Flexibility and early deployment**: DSI enables CO_2 to be transported from multiple ports across the three Baltic states and injected into the reservoir without waiting for a complete pipeline network to be built. Two Schwenk cement plants (in Latvia and Lithuania) already piloted CO_2 capture and will be ready on an industrial scale by 2030, while other plants can join later. Given the Baltic need to demonstrate storage capacity and meet EU ETS and national carbon neutrality targets, time-to-market is rated Critical, making this flexibility commercially and politically valuable.
- **Distance to storage site**: For the transboundary Estonian and Latvian Riga Port clusters, whose distance from the storage site makes early pipeline construction difficult to justify at initial CO_2 volumes, DSI offers a more flexible and scalable near-term transport solution until sufficient volumes or a fully integrated pipeline network becomes operational.
- **Licensing and administrative simplicity**: For distant transboundary Estonian emitters, DSI avoids the international administrative complexity that comes with building a transboundary pipeline network. Connecting these sources via pipeline would require more complicated international agreements and construction approvals, adding significant overhead in time and effort. By removing this requirement, direct injection allows the project to move through a simpler international regulatory process and can bring those sources closer to implementation sooner.
- **The proximity of the storage site to shore** (37 km from E6 well) and its shallow water depth (~36.5 m at wellhead) eliminates the need for a permanent offshore platform. This is a notable advantage, as offshore platforms are not only capital-intensive but can also create visual and environmental concerns for coastal communities and tourism.
- **The E6 storage site is located outside the Natura 2000 protected area.** In spite of different possible environmental problems in the Baltic Sea, the E6 storage site is located outside the Natura 2000 protected area (Marine Protected Area – MPA), therefore it will be much easier to get a permit and to prepare an EIA, if CO_2 storage is permitted in the Baltic Sea by HELCOM (ongoing process).
- **The oil exploitation license for the E6 site** is held by the oil company, which could be an advantage for E6's use for CO_2 storage, as oil exploitation is no longer supported by the EC.

Until now, the E6 licence holder has been interested in applying CO_2 storage in Latvia and Lithuania, and he conducted the first CO_2 injection experiments in the Baltic States in 2013, which were operated by his Lithuanian company, Minijos Nafta.

- **Job creation:** Implementing DSI would create and/or sustain jobs in port operations, shipping, vessel services, and subsea engineering at ports in Estonia, Latvia, and Lithuania. This would strengthen regional and national economies, which are important factors in technological solutions. Baltic ports are very much interested in new business opportunities and projects.

3.1.3 Main DSI barriers and risks

The following significant barriers and risks are identified for the Baltic Scenario:

- **National and international regulatory framework.** National, regional, and international regulations are the main barriers to implementing DSI technology. Latvia and Lithuania are not members of the London Protocol. For trans-border ship transport of CO_2, it is needed to implement permitting CO_2 storage regulations in the Baltic Sea geological structures by HELCOM (ongoing process since 2025). It is also needed to implement bilateral agreements with Latvia about the use of storage sites. In addition, detailed national permitting rules and regulations for offshore CO_2 storage in Latvia need to be developed. These regulations should also cover the relationships between oil licenses and CO_2 storage licenses, as well as detailed technical regulations for CO_2 transport and injection by ships. In all the Baltic States, land and marine planning for CCS projects and CCUS in industrial Strategy or plans are absent.
- **Environmental aspects**: The Baltic Sea has its own unique characteristics, and many environmental impacts are already being discussed in the HELCOM report, which is currently in draft form and under discussion by the HELCOM CCS Environmental Task Force and HELCOM countries. The Baltic Sea is a shallow, semi-enclosed, brackish system with limited water exchange with the North Sea through the Danish Straits. This results in long water residence times and slow ventilation of deep basins[12]. The Baltic Sea includes ecosystems with relatively low resilience to physical disturbance and chemical change, making them vulnerable to human activities associated with pressures. Marine Protected Areas (MPAs) are a key tool for addressing biodiversity loss in the Baltic Sea. The planned offshore storage area in Baltic Scenario E6 is located outside the above-mentioned MPAs. The shipping routes to the E6 storage site in the Baltic Sea could also be arranged outside the Baltic MPAs and could correspond to the available shipping routes.
- **Socio-economic impacts.** CO_2 storage projects in the Baltic Sea compete with many activities, including tourism, fishing, offshore wind parks, underground electrical cables and pipelines, and military areas. Because many of the most prospective storage sites extend across or lie close to national boundaries (such as the E6 storage site), socio-environmental criteria require that site selection be coordinated at a regional scale. To be accepted by the public, the storage sites should avoid areas of high social sensitivity, and local communities and sea users should be engaged early and transparently informed about risks, safeguards, and potential benefits[13]. According to the non-technical data collected and reported by the CCUS ZEN project for the Baltic Sea Region, public acceptance of CCS technology in Estonia and Latvia is medium, while in Lithuania it is low.

[12] Leppäranta, M., & Myrberg, K. (2009). *Physical oceanography of the Baltic Sea.* (Springer-Praxis books in geophysical sciences). Springer.

[13] Witte, K. (2021). Social acceptance of carbon capture and storage (CCS) from industrial applications. *Sustainability, 13*(21), 12278. https://doi.org/10.3390/su132112278.

- **Operational risks.** There is no Baltic oil and gas or drilling company which can operate the offshore storage site. The nearest regional companies are in Poland and Denmark, which are currently busy developing their national CO_2 storage projects. International investment, operations, and drilling companies will be required for the development of the Baltic offshore site.

3.1.4 Regional recommendations

Given the drivers and barriers identified, the following recommendations are proposed to manage risks and build replicability of the DSI application in possible scenarios for CCS deployment in the Baltic Sea:

Regulatory and Policy:

1. It is possible that HELCOM will implement CCS regulations for the Baltic Sea, where CO_2 storage will be permitted with limitations in less-impacted areas and outside MPA areas, as is the case for the E6 structure. The regulatory framework for CO_2 transport will soon be addressed at the EU level, as the European Commission is now working on a corresponding regulation. It is likely that Latvia, Estonia and Lithuania will directly adopt the EU regulations for CO_2 transport as they come into force and will most likely remove the need for national frameworks. However, given the specifics of the Baltic Sea and HELCOM, CO_2 transport regulations should also be adopted by HELCOM. Engaging with national governments and competent authorities, which implement all HELCOM regulations, would further enable the anticipation of compliance requirements.

Environmental Aspects:

2. According to Latvian environmental law, every CO_2 storage site permit must be submitted with an EIA. The EIA should specifically address all environmental impacts on the ecosystem and biota
3. The possibility of establishing a protection zone around the injection site, which could serve as a marine sanctuary and provide an environmental co-benefit, should also be regulated by HELCOM.

Socio-Economic Impacts

4. CO_2 carriers almost permanently over the injection site is a legitimate concern for recreational and commercial navigation, and continuous engagement with operators and local municipalities should begin early.
5. Direct dialogue with shipping companies, which may feel affected in their activities, and regulatory authorities could be important. A clear communication strategy that explains operations and strategy, along with the employment benefits for the region, will be key to maintaining broad social acceptance.

Stakeholder engagement

6. Environmental and socio-economic issues impose a stakeholder engagement strategy that should start during EIA scoping and continue through pilot operation. The plan should cover fisheries, tourism, navigation users, municipalities, port authorities and environmental NGOs, using regular briefings, published exclusion-zone maps, vessel schedules, and a grievance channel.

7. Mitigation measures could be regulated by HELCOM and may include seasonal scheduling, noise monitoring, local procurement, employment commitments, and compensation when navigation routes are temporarily restricted.

Maturity and time-to-market

8. Due to national climate commitments and EU ETS compliance pressures, rapid development in the Baltic states is critical, making it essential that Latvian authorities address policies and permitting barriers without delay. A pilot project is both expected and necessary, not only to demonstrate storage capacity but to validate the site under real injection conditions before any commercial-scale operations. DSI is particularly well-positioned in this context because of its flexibility and early deployment. However, the direct injection solution and the new satellite RSS monitoring method are not yet mature and have not yet been demonstrated. Thus, technological developments in the DSI solution are urgently needed, and a techno-economic demonstration of its feasibility is required before 2030 to be compatible with the timeline for deploying CCS in the Baltic Region.

Transitioning of the Baltic Scenario into the extended Baltic Scenario

9. For the Baltic Sea scenario, including emitters from three countries and large distances from Estonian ports and the Riga port, the spatial distribution of sources across the three countries, the TEA presented in D3.1 indicates that the conventional ship scenario (SHIP) is the most cost effective for the Baltic countries.
10. Selecting DSI over SHIP would therefore have to be justified on grounds beyond cost, such as avoiding the upfront investment exposure of a dedicated offshore platform, phasing flexibility, or alignment with broader logistical or regulatory constraints at the storage site.
11. However, if the CO_2 supply from Estonia, Latvia and Lithuania is not high enough to support low costs per tonne of CO_2 stored in the offshore E6 structure, this Baltic DSI scenario could be extended to CO_2 emitters in Finland and Sweden, which are now planning to transport their captured CO_2 emissions to the North Sea. Such planning is most likely if onshore CO_2 storage sites in Latvia are developed and Latvian and North-Lithuanian emitters choose more nearby onshore CO_2 storage sites.

3.2 Black Sea

3.2.1 Regional Context

Romania and Ukraine are assessed jointly in the CTS project because they form part of the same maritime setting and share specific Black Sea conditions relevant to DSI deployment. This joint treatment nevertheless imposes important limitations on the analysis. The two countries differ substantially in regulatory status, climate-mitigation obligations, CCS market maturity, access to finance and infrastructure, and in the case of Ukraine, the consequences of the ongoing war for industrial activity, maritime security, asset accessibility and project implementation. The combined regional assessment should therefore be interpreted as a Black Sea-level synthesis rather than as evidence that the barriers, opportunities or deployment conditions are equivalent in Romania and Ukraine. Where these differences affect the conclusions, they are identified in the regional discussion.

Policy and decarbonization framework

Both Romania and Ukraine are committed to reducing GHG emissions and are parties of important international agreements. Romania signed the UNFCCC in 1992 (ratified in 1994) and the Kyoto Protocol in 1999 (ratified in 2001, as the first Annex 1 country to do so), while Ukraine ratified the

UNFCCC in 1996, the Kyoto Protocol in 2004, and the Paris Agreement in 2016. Although neither country has a comprehensive dedicated CCS strategy yet, Romania's approach centres around its 2011 CCS Directive (Emergency Governmental Ordinance no. 64), while Ukraine currently regulates CCS permitting through its Code of Subsoil.

Ukraine is committed to reducing GHG emissions by 65% by 2030 compared to 1990 levels under its updated Nationally Determined Contribution (NDC, 2021). The government approved the NECP to 2030 in June 2024, aligned with EU Regulation 2018/1999 and Energy Community obligations. The Energy Strategy of Ukraine targets climate neutrality in the energy sector by 2050 and economy-wide climate neutrality by 2060. Ukraine's regulatory framework is reinforced by the Law on Monitoring, Reporting and Verification (MRV) of Greenhouse Gas Emissions, ongoing preparations for a national Emissions Trading System (ETS), and the 2023 establishment of the State Fund for Decarbonization and Energy-Efficient Transformation. Regarding CCS, alignment with the EU legislation is still in progress.

Romania's target is considerably more ambitious in the near-term with an 85% reduction in GHG emissions by 2030 compared to 1990 levels, which according to the NECP for 2025-2030 (last updated October 2024), had already in 2022. The plan sets a further objective of 96% net GHG emission reduction by 2040 and net zero by 2050.

Under the Net Zero Industry Act (NZIA), Romanian oil and gas producers collectively hold a CO_2 injection quota of 10.25 Mt/year until 2030. The national CCS framework is anchored in the CCS Directive (2009/31/EC), transposed via Emergency Governmental Ordinance no. 64/2011, with NAMRMPSG as the competent authority for geological storage and ANRE regulating CO_2 transport. Ordinance 139/2024 amended the CCS law to streamline permitting, allowing storage permits to be issued directly to existing hydrocarbon site owners without a new exploration procedure if they can demonstrate safe storage suitability and sufficient site-characterisation data.

CO_2 emitters and capture

As established in D3.1, the Ukrainian CCS scenarios focus on major stationary emitters located in the Odesa the Mykolaiv regions, selected due to their proximity to the Black Sea, established industrial infrastructure, and concentration of emissions-intensive activities. Amongst the selected emitters, cement sector represents the largest share of CO_2 emissions, accounting for approximately 3.54 Mt/yr CO_2. This includes 1.41 Mt/yr CO_2 from facilities in Odesa and 2.13 Mt/yr CO_2 from Mykolaiv. Given the scale and concentration of emissions, the cement industry has been identified as a priority sector for early deployment of carbon capture technologies in Ukraine. These emissions provide a sufficiently large and reliable CO_2 stream to support the development of a regional CCS value chain, including capture, transport, and offshore storage solutions in the Black Sea region.

In the Romanian scenario (see D3.1 for details), two industrial clusters Călărași and Constanța are selected with a total CO_2 emission of 2.18 Mt/yr. Călărași cluster has 2 emission sources, a glass factory and a steel producer, which together emitted 0.15 Mt in 2023. Constanța cluster on the other hand has 5 industrial installations, a cement plant (Medgidia), a thermo-energetic plant (Constanța), a thermo-energy plant (Midia), a refinery (Petromidia) and a lime facility (S.C: Celco S.A.). Together, in 2023 these 5 installations emitted a total of 2.03 Mt CO_2. For the techno-economic analysis it was assumed that these installations will emit the same amount of CO_2 as in 2023.

CO_2 storage site

The primary CO_2 storage sites in the Ukrainian scenario are offshore Holitsyna and Shtormove depleted gas and gas-condensate fields in the Black Sea. These are located within the Karkinite–North Crimean

Depression as shown in Figure 7. The target storage interval in both fields is the П-XI reservoir of Lower Paleocene age, composed mainly of fractured limestones and associated carbonate and terrigenous sediments. Reservoir depths range from approximately 986 m to 2,155 m, with average thicknesses of 80–85 m, while regional Eocene clay and marl formations provide an effective caprock seal. Storage capacity assessments indicate a most-likely capacity of approximately 105 Mt CO_2 for Holitsyna and 100 Mt CO_2 for Shtormove, resulting in a combined storage potential of around 205 Mt CO_2. The offshore location, existing hydrocarbon infrastructure, and significant storage capacity make these fields promising candidates for supporting long-term CCS deployment and the development of a regional CO_2 transport and storage network in Ukraine.

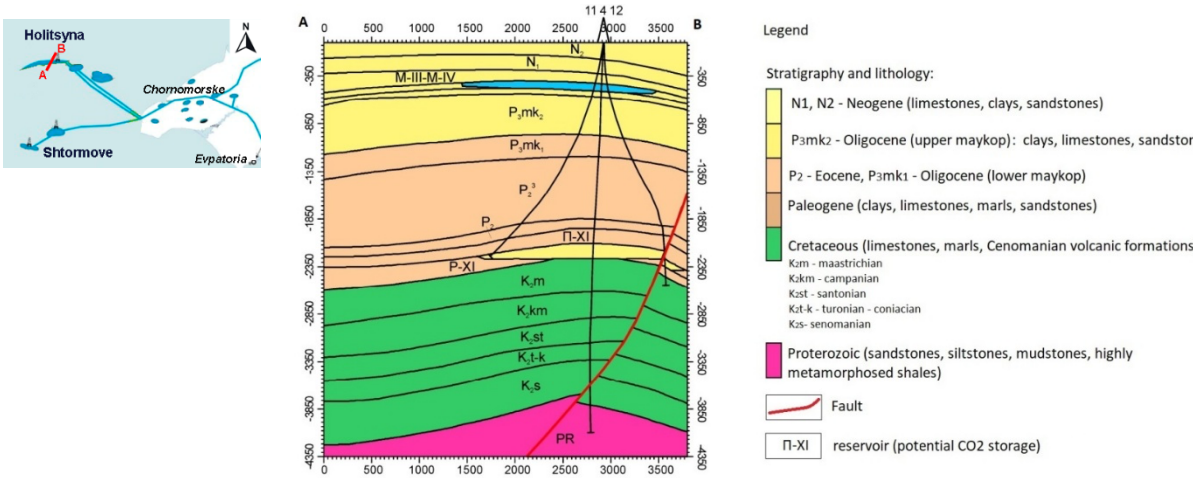


Figure 7. Stratigraphy in area of the Holitsyna field potential storage site in the Ukraine scenario.

In Romanian scenario the offshore storage solutions available are four deep saline aquifers (Iris, Venus, Tomis, Lotus) and three nearly depleted hydrocarbon fields (Lebada Est, Lebada Vest, Sinoe) with complete details described in D2.1. For the techno-economic analysis, only 3 sites have been selected, Iris, Lotus and Tomis, potential deep saline aquifers. For the three sites, the Albian formation was selected as best storage reservoir, composed of quarzitic sandstone with calcareous cement (Iris), calcareous sandstones with thin intercalations of silty clays (Lotus) and grey sandstones with calcareous cement (Tomis). The seal formations are diverse, Senonian marly formations for Iris structure, compact blackish Albian clays for Lotus and compact blackish Cenomanian marls for Tomis. Although the storage capacities are limited, it is still sufficient to accommodate the CO_2 captured from the envisaged industrial clusters for a 30-year period. The largest CO_2 storage capacity is estimated for Tomis structure at 33 Mt CO_2, followed by Lotus and Iris, both with around 29 Mt storage capacity.

Transport configuration description

The Ukrainian scenario evaluates the conventional ship (SHIP), pipeline (PIPE) and Direct Ship Injection (DSI) configurations to transport CO_2 to the storage sites (see Figure 8). The PIPE scenario includes a hybrid onshore-offshore pipeline network of approximately 293 km, connecting Mykolaiv and Odesa ports with the Holitsyna and Shtormove storage fields. The SHIP scenario uses conventional CO_2 carriers transporting CO_2 from both ports to the Holitsyna field, with onward transfer to Shtormove via offshore pipeline, covering around 290 km. The DSI scenario employs two ships equipped with direct injection technology, transporting CO_2 directly from the ports to the respective storage sites without intermediate pipeline infrastructure, with a combined route distance of approximately 590 km. Together, these scenarios evaluate alternative transport configurations tailored to Ukraine's offshore storage opportunities and existing logistical conditions.

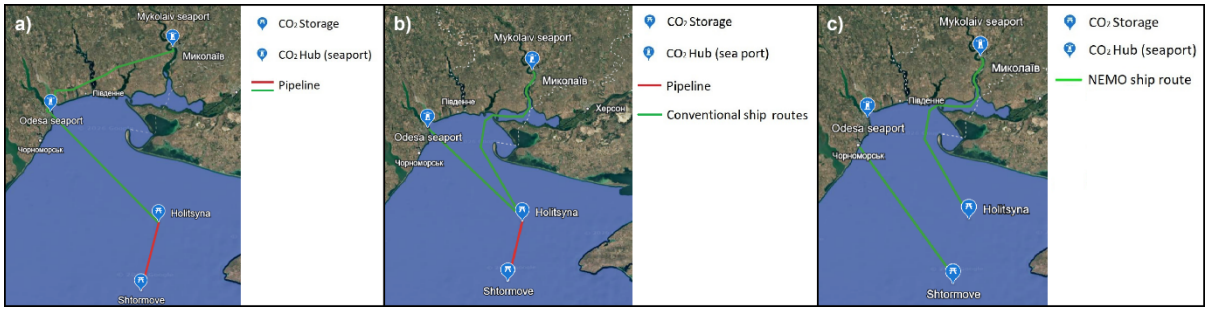


Figure 8.Transport configuration of Ukrainian scenario: a) PIPE, b) SHIP and c) DSI.

Romanian scenario (illustrated in Figure 9) involves capturing CO_2 from both the industrial clusters (Călărași and Constanța) and transporting it onshore using a multimodal system. This consists of small pipelines (10 km in total), rail connections (about 30 km), and fluvial ship/barge transport on the Danube (185 km) to the port. From the port, the offshore segment is designed and evaluated for all three options, PIPE (73 km in total), SHIP, and DSI (both with 51 km sailing distance), with CO_2 ultimately stored in offshore solutions such as deep saline aquifers and depleted hydrocarbon fields. The detailed transport configuration is as described in deliverables D3.1 and D2.1.

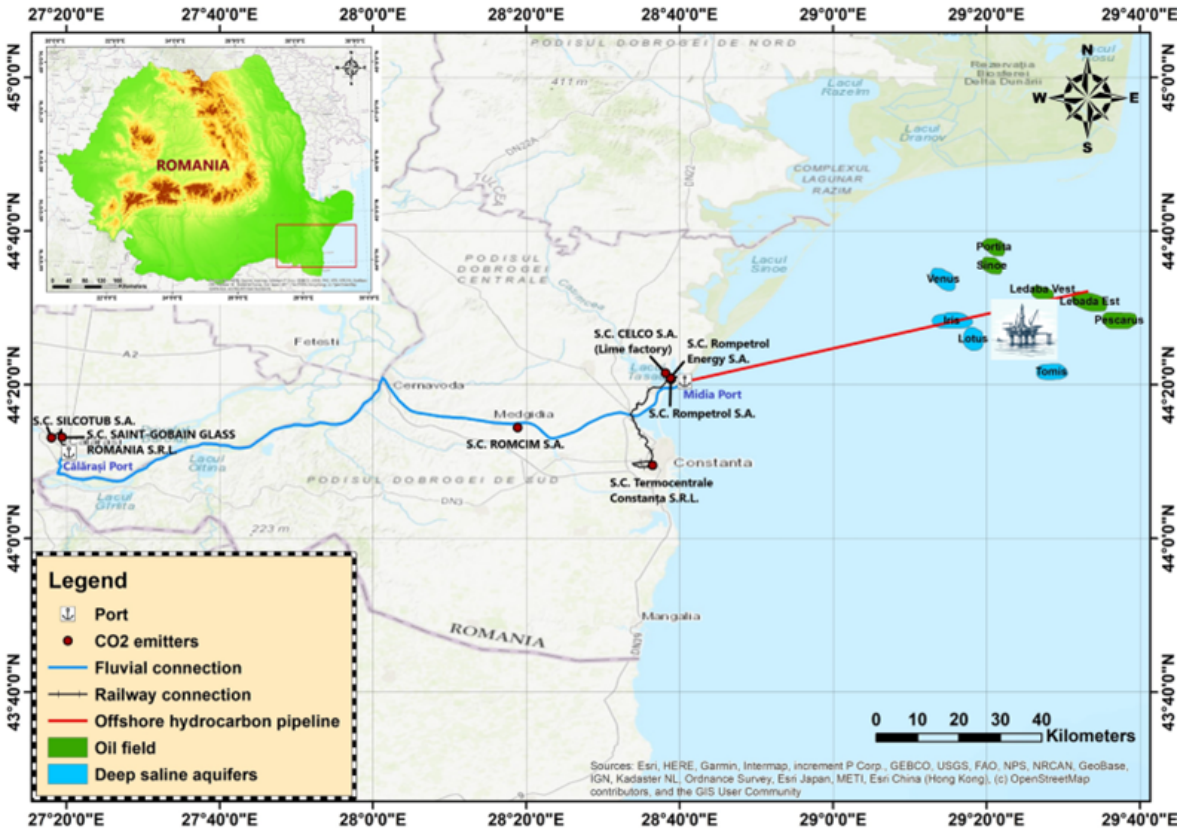


Figure 9. Schematic of CTS Romanian scenario transport network.

3.2.2 Main DSI drivers and opportunities

Regional response of categorized guiding questions for qualitative assessment for the Black Sea region is represented in the Figure 10. Figure records the regional response to the questions as well as the colour code representing relevance of each question for the deployment of DSI in the region.

Figure 11 presents the cumulative relevance for the Black Sea region (Romania and Ukraine) across the main categories influencing DSI deployment based on the scoring awarded in Figure 10. The results indicate that regulatory environment, socio-economic impacts, technical feasibility, infrastructure and

logistics, maturity and time-to-market, and site-specific geological factors all achieve important relevance, while environmental aspects show minor relevance for DSI deployment. This suggests that DSI deployment in the Black Sea is primarily influenced by regulatory, technical, logistical, and market-readiness considerations rather than environmental constraints.

Guiding questions	Black Sea	
	Regional status	Regional relevance
Regulatory environment		
Regulations for CO2 transport by ship exists?	No	
Are ship permits faster than offshore pipelines?	Yes	
Are absence of pipeline regulations an opportunity?	Yes	
Environmental aspects		
Are noise impacts from ships an issue?	Yes	
Are pipelines and platforms a concern?	Undefined	
Can potential CO2 leaks compromise habitats?	Undefined	
Is direct injection an environmental concern?	No	
Socio-economic impacts		
Are the visual impacts of platforms a concern?	No	
Are there possible conflicts with stakeholders?	Yes	
Does direct injection favour job creation?	Yes	
Is there higher social acceptance for reversible solutions?	Yes	
Technical feasibility		
Are the maritime conditions challenging?	No	
Are there long non-operational periods due to weather?	No	
Is there continuous supply of CO2	Undefined	
Is continuous injection favoured by injectivity?	Undefined	
Infrastructure & Logistics		
Do CO2 sources favour transport to a port?	Yes	
Are many small-scale CO2 sources identified?	Yes	
Is the platform technically justified for the expected capacity?	Undefined	
Maturity & time-to-market		
Is rapid deployment needed?	Yes	
Is the pilot phase expected?	Yes	
Does direct injection accelerate deployment?	Yes	
Site-specific geological factors		
Is the reservoir injectivity suitable for intermittent injection?	Undefined	
Will initially only 1–2 wells be available?	Yes	
Is the storage site remote (e.g., deep water)?	No	

Figure 10. Regional status of guiding questions along with their relevance for Black region (Colour code - Green: No relevance, Lime-green: Minor relevance, Yellow: Important relevance, Red: Critical relevance, double colour: possible lower relevance (left) with possible upper relevance (right)).

The relatively high scores for maturity and time-to-market reflect the need for rapidly deployable CCS solutions that can support decarbonization objectives in Romania and Ukraine. Likewise, infrastructure and logistics are important due to the availability of major Black Sea ports and the concentration of industrial emitters near coastal regions. Technical feasibility and site-specific geological factors also rank highly, reflecting the presence of prospective offshore storage formations in relatively shallow waters and the suitability of ship-based injection concepts for early deployment. Environmental

aspects receive a lower score because DSI can reduce seabed disturbance and the need for extensive offshore infrastructure compared with conventional pipeline-based solutions.

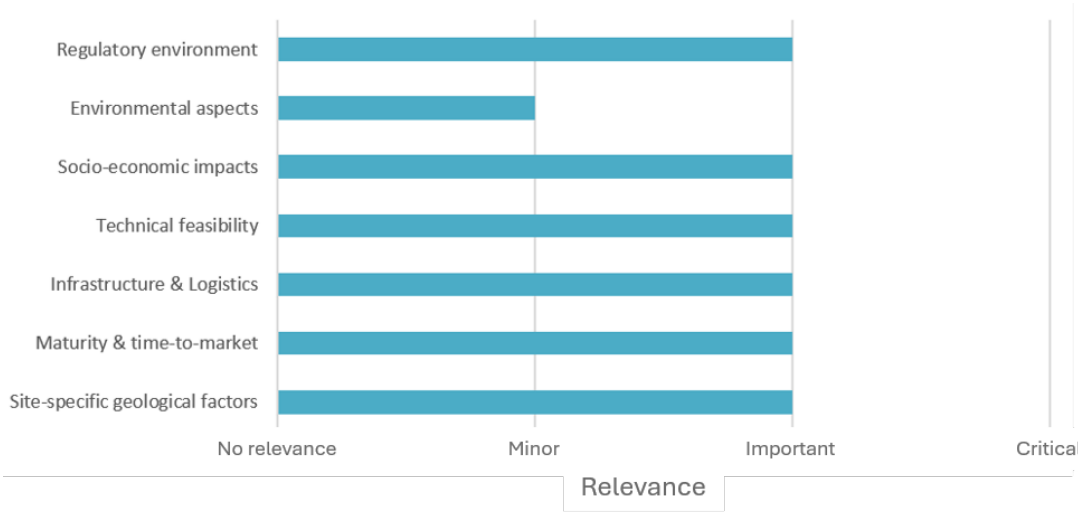


Figure 11. Cumulative relevance of each guiding category related to DSI implementation in Black Sea region.

The main drivers for DSI in the Black Sea region are:

- **Rapid deployment potential:** DSI can accelerate CCS implementation by avoiding the need for extensive pipeline infrastructure, supporting decarbonization targets and future compliance with EU climate policies, NZIA and ETS requirements (Romania), and CBAM-related pressures (Ukraine).
- **Simplified permitting:** Compared with pipeline systems, DSI avoids complex land acquisition, cross-border pipeline approvals, and some security-related permitting challenges.
- **Existing port infrastructure:** Black Sea ports provide a strong foundation for developing regional CO_2 hubs and handling CO_2 transport operations both in Romania and Ukraine.
- **Favourable offshore conditions:** Storage sites are located in relatively shallow waters, potentially allowing direct injection without permanent offshore platforms during early project phases.
- **Reduced environmental footprint:** DSI can minimise seabed disturbance and reduce interference with fisheries and marine habitats compared with large-scale pipeline developments.
- **Operational flexibility:** Ship-based transport allows multiple emission sources to be connected progressively and can serve as a transitional solution before the development of integrated CCS networks.
- **Economic opportunities:** DSI can create value through port activities, shipping services, monitoring operations, and offshore engineering while strengthening regional maritime industries.

3.2.3 Main DSI barriers and risks

Despite the favourable overall assessment, several barriers/challenges remain important for DSI deployment in the Black Sea region.

- **Regulatory uncertainty:** The absence of dedicated frameworks for CO_2 shipping, offshore storage operations, long-term liability, and transboundary CO_2 transport remains one of the most significant challenges.

- **Limited data & geological knowledge:** Additional reservoir characterization, injectivity testing, dynamic modelling, and well integrity assessments are required to confirm long-term storage performance both in Romania and Ukraine.
- **CO_2 supply uncertainty:** Future CCS clusters are still under development, creating uncertainty regarding captured CO_2 volumes and transport requirements.
- **Higher operational costs:** Although DSI reduces initial infrastructure investment, ship-based transport may be less cost-competitive than pipelines at larger transport volumes.
- **Maritime security risks:** Black Sea geopolitical conditions introduce additional uncertainties related to shipping operations, insurance, and project financing.
- **Stakeholder and environmental considerations:** Potential interactions with fisheries, shipping routes, and protected marine areas require careful planning and environmental assessment.
- **Market immaturity:** CCS remains at an early stage in the region, requiring stronger policy support, financial incentives, demonstration projects, and public engagement.

Overall, the strongest case for DSI in the Black Sea region lies in its ability to provide a flexible, rapidly deployable, and infrastructure-light CCS solution, while the main challenges relate to regulatory development, geological uncertainty, and the need to establish a mature CCS market and investment framework.

3.2.4 Regional recommendations

Given the drivers and barriers identified for the Black Sea region, encompassing both Romania and Ukraine, the following recommendations are proposed to support the safe, efficient, and replicable deployment of DSI as part of future CCS value chains.

Regulatory and Policy

1. Develop a clear regulatory framework for CO_2 shipping and offshore storage. Both Romania and Ukraine currently lack comprehensive regulations governing CO_2 transport by ship, offshore injection operations, long-term liability, and transboundary CO_2 transport. Regulatory alignment with evolving EU CCS policies should be prioritised, particularly for Ukraine as part of its EU integration process.
2. Establish pilot-project permitting pathways. Regulators should consider creating dedicated demonstration or regulatory sandbox frameworks that allow pilot DSI projects to progress under simplified permitting procedures while maintaining environmental and safety standards.
3. Promote cross-border cooperation. As future Black Sea CCS networks may involve transboundary transport and shared storage infrastructure, early cooperation between national authorities, port operators, and storage developers is recommended.

Environmental Aspects

4. Conduct comprehensive marine environmental assessments (EIA). EIAs should evaluate potential impacts on fisheries, shipping routes, protected marine areas, and marine ecosystems, including the unique geochemical conditions of the Black Sea.
5. Assess CO_2 behaviour under Black Sea conditions. The anoxic nature of deeper Black Sea waters warrants dedicated geochemical and plume migration modelling to improve understanding of potential leakage scenarios and environmental impacts.
6. Minimise seabed disturbance. Where feasible, DSI should be favoured during early project phases as it reduces the need for extensive subsea pipelines and associated seabed impacts.

Socio-Economic Impacts and Stakeholder Engagement

7. Develop an early stakeholder engagement strategy. Consultation should begin during project planning and continue throughout development, involving fisheries, shipping operators, port authorities, municipalities, environmental organisations, and local communities.
8. Communicate the economic benefits of CCS and DSI. Particular emphasis should be placed on employment opportunities in port operations, logistics, shipping services, monitoring activities, and offshore engineering.
9. Coordinate with maritime users. Potential conflicts with fisheries and commercial navigation should be managed through transparent communication, operational planning, and clearly defined safety zones around injection sites.

Technical Feasibility and Infrastructure

10. Develop CO_2 hub infrastructure at major Black Sea ports. Constanța, Odesa, Mykolaiv, and other strategic ports could serve as regional CO_2 aggregation hubs supporting future transport and storage networks.
11. Confirm reservoir performance through testing. Additional reservoir characterization, injectivity testing, dynamic modelling, and well integrity assessments are required before commercial deployment of DSI.
12. Assess operational flexibility requirements. Given uncertainties regarding future CO_2 supply profiles, operators should evaluate the need for intermediate buffer storage and campaign-based injection strategies.
13. Integrate smaller emitters into CCS clusters. DSI can provide a flexible mechanism for connecting dispersed and smaller industrial sources before larger transport networks become available.

Maturity and Time-to-Market

14. Prioritise pilot-scale DSI demonstration before 2030. The urgency of decarbonisation targets, EU ETS requirements, CBAM implementation, and industrial competitiveness creates a strong case for early demonstration projects in the Black Sea region.
15. Accelerate storage site characterization. Reservoir appraisal programmes should be prioritised over the coming years to reduce uncertainty regarding storage capacity, injectivity, and long-term containment performance.
16. Support technology development and demonstration. Although DSI offers significant advantages for early deployment, the technology remains at a relatively early stage of commercial maturity and requires further demonstration under real operating conditions.

Transitioning from Early-Stage to Long-Term CCS Networks

17. Consider DSI as a transitional solution. While DSI offers flexibility, reduced infrastructure requirements, and faster deployment, pipeline transport may become more economically favourable as CO_2 volumes increase and regional CCS networks mature.
18. Use DSI to enable early CCS deployment and storage validation. DSI can provide a practical pathway for demonstrating storage resources, developing operational experience, and connecting early emitters before large-scale pipeline infrastructure becomes justified.
19. Develop a phased CCS roadmap for the Black Sea with a staged approach combining early DSI deployment with progressive development of shared transport.

3.3 North Sea

3.3.1 Regional Context

Policy and decarbonisation framework

Key elements of Norwegian decarbonisation strategy are listed in D5.1. Here it is important to state that Norway CO_2 tax was introduced in 1991. The national CO_2 emission taxes in Norway has since then been equalized and from 2021 its number was set to gradually increase to 2 000 NOK/t by 2030. In 2024, the government issued "Grønt industriløft 2.0" in which the role of the industrial policy is to maximize the value creation in the Norwegian economy within what is "*socially, environmentally and economically sustainable – without exceeding the boundaries of the Earth*"[14]. Within this policy document, the same ambitions were stated again. These included an emission reduction of 55% in 2030 (compared to the 1990 levels), as well as realizing green industry projects and creating attractive jobs. They also included increasing the export of goods by 50% (excl. oil and gas) within 2030, and reducing the vulnerability baked in central value chains associated with the green shift.

Both in Norway and Denmark, storage regulations are fully in place. In Norway a license in accordance with the CO_2 storage regulations serves as the authorization for exploration and exploitation of a subsea reservoir for injection and storage of CO_2 on the Norwegian Shelf. An exploitation license provides an exclusive right to store CO_2 in the area covered by the license. A full overview of legal documents and current list of exploitation and exploration licenses may be found on Norwegian Offshore directorate website[15].

CO_2 emitters and capture

As established in D2.1 and D3.1, large number of emitters, both in Norway and Denmark will need a carbon capture solution. One of the key complications, especially in Norway is a geographical spread of emissions along the coastline and their relatively small size. Out of all the facilities listed by Norwegian Environment Agency[16] only 2 emitters have more than 1 Mt/yr emissions, 4 more in the range of 0.5 to 1 Mt/yr and 20 more in the range of 0.1 to 0.5 Mt/yr with many more on the scale of 10s of thousands of t/yr and less. This complicates gathering logistics and significantly increases costs of capture.

CO_2 storage sites

A large number of storage sites have been identified and are currently in various development stages[15]. The storage atlas estimates total storage capacity in aquifers alone on the scale of 10th of Gigatonnes, however the actual injectivity and pressure balancing[17] will reduce the number. Aquifers are generally high permeable sandstones[18] of mostly Jurassic with few of Paleogene and Neogene periods. The conceptual sketch of aquifers location for the Norwegian North Sea from storage atlas[18] is shown in Figure 12.

[14] https://www.regjeringen.no/no/dokumenter/veikart-2.0-gront-industriloft/id2996119/?ch=2
[15] CO2 storage - The Norwegian Offshore Directorate
[16] The Norwegian PRTR - Pollutants to air and water and generated transfers of waste, Emissions
[17] https://doi.org/10.1016/j.ijggc.2026.104610
[18] Introduction - The Norwegian Offshore Directorate

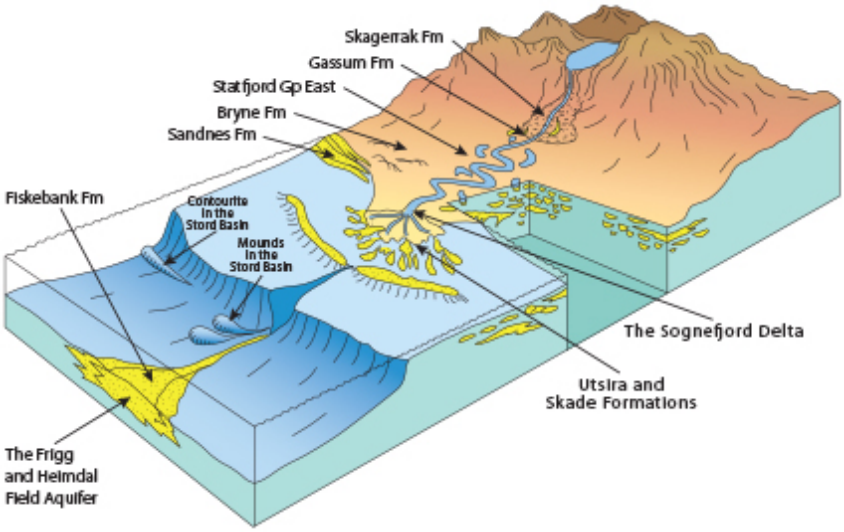


Figure 12. Conceptual sketch showing location of aquifers relative to depositional systems from SoDir storage atlas.

Transport configuration description

In the CTS study the majority of the cases are based on CO_2 carriers. Only one segment in Danish North Sea looked into using carriers to port followed by pipeline (using either existing pipeline or, at least, established pipe corridor) to offshore storage site. This solution is similar to the one used by Northern Lights.

Generally current license owners in Norwegian North Sea rely on shipping solutions to bring CO_2 to Norway. It seems that a concept of CO_2 delivery to offshore locations directly without using intermittent base like in the Northern Light case is currently dominating.

3.3.2 Main DSI drivers and opportunities

Regional response of categorized guiding questions for qualitative assessment for the North Sea region is represented in the Figure 13. Figure records the regional response to the questions as well as the colour code representing relevance of each question for the deployment of DSI in the region.

Guiding questions	North Sea	
	Regional status	Regional relevance
Regulatory environment		
Regulations for CO2 transport by ship exists?	Yes	
Are ship permits faster than offshore pipelines?	Yes	
Are absence of pipeline regulations an opportunity?	No	
Environmental aspects		
Are noise impacts from ships an issue?	No	
Are pipelines and platforms a concern?	No	
Can potential CO2 leaks compromise habitats?	No	
Is direct injection an environmental concern?	No	
Socio-economic impacts		
Are the visual impacts of platforms a concern?	No	
Are there possible conflicts with stakeholders?	Yes	
Does direct injection favour job creation?	No	
Is there higher social acceptance for reversible solutions?	No	
Technical feasibility		
Are the maritime conditions challenging?	Yes	
Are there long non-operational periods due to weather?	Undefined	
Is there continuous supply of CO2	Undefined	
Is continuous injection favoured by injectivity?	Undefined	
Infrastructure & Logistics		
Do CO2 sources favour transport to a port?	Yes	
Are many small-scale CO2 sources identified?	Yes	
Is the platform technically justified for the expected capacity?	Undefined	
Maturity & time-to-market		
Is rapid deployment needed?	Yes	
Is the pilot phase expected?	Yes	
Does direct injection accelerate deployment?	Yes	
Site-specific geological factors		
Is the reservoir injectivity suitable for intermittent injection?	Undefined	
Will initially only 1–2 wells be available?	Yes	
Is the storage site remote (e.g., deep water)?	No	

Figure 13. Regional status of guiding questions along with their relevance for North Sea region (Colour code - Green: No relevance, Lime-green: Minor relevance, Yellow: Important relevance, Red: Critical relevance).

Figure 14 shows cumulative relevance scores of each category for the North Sea scenario based on the scoring awarded in Figure 13. Regulatory environment, socio-economic impacts and maturity and time-to-market are ranked highest with neither critical nor irrelevant categories identified.

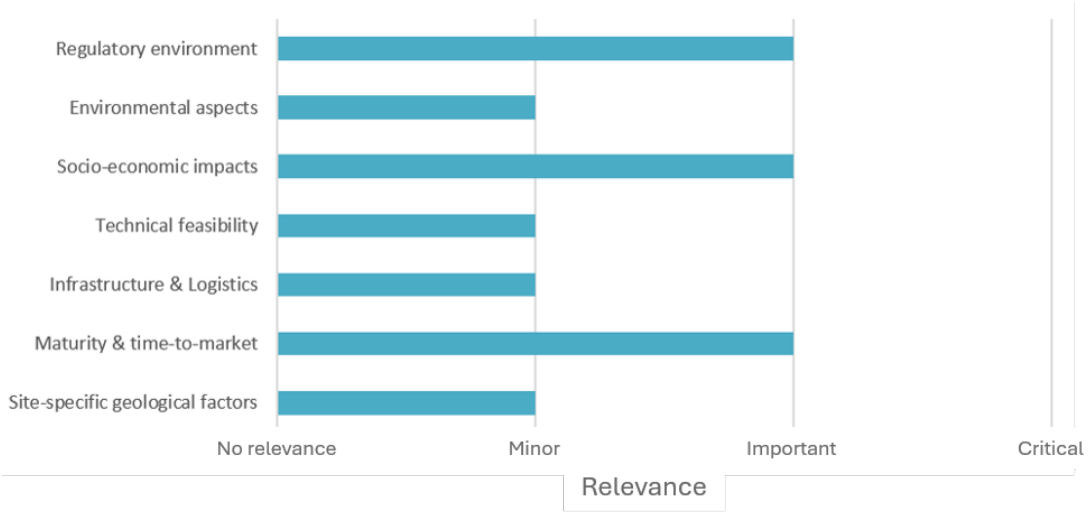


Figure 14. Cumulative relevance of each guiding category related to DSI implementation in North Sea region.

The main drivers for DSI in the North Sea are:

- **Business case and costs:** While storage sites in Norway can provide storage on hundred megatons to gigaton scale, currently the required volume to justify building major infrastructure simply do not exist. On the early development stage more lean flexible solutions are needed and DSI can become an adequate solution in that context.
- **Regulatory framework:** Is well established and based on existing experience in O&G operations in general and for oil shuttle tankers in particular. With a large number of competing economic activities on the shelf and many different pipelines, DSI may be easier to permit and roll out than pipeline options. Discussions with authorities has not revealed any critical issues that will prevent DSI on the Norwegian Shelf.
- **Distance to storage site**: Vast majority of CO_2, at least for Norwegian sector, will have to come from European capture sites. Even in case of the local industry – it is widely spread along the Norwegian cost line. Either a system with a centralised aggregation of captured CO_2 is needed (likely similar to Northern Lights), an injection platform (complex and expensive especially when manned) or DSI solution can be utilized. The TEA in D3.1 shows that DSI offers the lowest investment costs for the storage operator and represents the most flexible and easily scalable solution.
- **Job creation**: Implementing DSI or SHIP configurations, when compared to the pipeline options, will support shipping and energy sector - key industrial sectors for Norway.

3.3.3 Main DSI barriers and risks

Several barriers have been however identified.

- Although the ship design and all critical components are based on existing technological solutions, there are uncertainties and risks associated with the operational regularity, compared to the mature pipeline solution. Nevertheless, Project Greensand is developing a concept in which the ship *Carbon Destroyer 1* carries liquefied CO_2 to the Nini offshore storage site, where the vessel remains dynamically positioned and uses onboard pumping and conditioning equipment to transfer pressurised CO_2 through a flexible offshore injection system to the Nini A platform and a converted injection well. The concept therefore combines

maritime transport with direct ship-to-reservoir injection, avoiding the need for a separate offshore CO_2 storage terminal[19]. Commercial operations are scheduled to begin in 2026.

- Currently storage operators control the whole value chain, which somewhat reduces its flexibility potential. Third party access to use existing storages will open up the market for transport and storage and make CCS a more competitive and flexible market driven by competition for the best solutions.
- Metocean conditions. Storm in the North Atlantic may create periods where DSI vessels would not be able to connect or inject. The same applies to conventional CO_2 vessels that many not be able to dock to platforms in bad weather conditions. The potential delays in injection may be compensated by either larger intermittent storage in ports, lower average ship utilisation and higher maximum injectivity allowing to compensate for delays. The economics of this is included in a regularity factor based on regularity data for oil shuttle tankers. In general, the regularity used is 90%, vs 96-97 % & for oil shuttling.

3.3.4 Regional recommendations

Based on the drivers and opportunities as well as risks the following may be recommended for this region.

Regulatory and Policy:

1. As mentioned, in Norway, the regulations and policy for CCS is heavily based on petroleum activity creating what seems at time as unnecessary restrictions and complications as the nature of CO_2 and hydrocarbons are different. CO_2 is neither flammable nor explosive. Based on ongoing projects, operational experience and consultations with stakeholders, streamlining and simplifying the regulations where possible due to different nature of CO_2 compared to petroleum fluids, may be advised to reduce costs and project approval and documentation requirements.
2. From the **environmental perspective** there are no major differences between using conventional carbon dioxide carriers and intermittent storage and DSI, although in DSI the vessel will remain longer using dynamic positioning over the injection well, implying higher energy consumption (and possibly associate CO_2 emissions) and more imposed noise (which could be relevant for cetaceans).

Environmental aspects

3. The creation of a protection zone around the injection site could act as a marine sanctuary, creating an environmental co-benefit.

Socio-Economic Impacts

4. CCS in general is an important industrial activity for “post oil” Norway. DSI will utilize Norway’s leading and well-developed offshore operational experience and be a new activity for the shipping industry, that can provide and important driver for Norway’s economy.
5. A well-established dialogue between operators of different storage licences and competing economic activities in the area is vital for a well-functioning economical system of the continental shelf. Providing a flexible regime to allow for utilization of multiple storage sites will reduce the storage risk and mitigate storage liabilities for the CO_2 license holders. This will

[19] NOV secures contract to supply innovative CO_2 transfer solution for Project Greensand. https://www.nov.com/news/nov-secures-contract-to-supply-innovative-co2-transfer-solution-for-project-greensand.

contribute to reduce storage costs and make Norway more competitive and attractive compared to our competitors in other areas of the North Sea.

Stakeholder engagement

6. Linking CO_2 value chain together requires solid engagement and a good dialogue between different stakeholders. Considering above mentioned potential competition with other economic activities establishing a platform for a regular stakeholder dialogue is recommended.

Metocean conditions

7. North Sea is a rough operational environment with frequent storms especially in winter season. However, decades of oil shuttle tanker operations provide a solid basis for design and operation of CO_2 carrier vessels, and the offloading and injection solutions are based on existing solutions for oil, adapted to CO_2 conditions.

Maturity and time-to-market

8. The time to market for DSI is potentially short compared to solutions with intermittent storage and pipelines. In principle, about 3 years for new builds and 1-2 years for conversion of existing shuttle tankers. Same as conventional vessels, DSI do not require long lead time for approvals and sea bottom surveys such as pipelines.

Transitioning early-stage option

9. Currently in Norway increasing number of the operators are considering DSI due to need to transport the emissions from Europe, as the volumes required to justify the pipeline are not currently available. Batch injection requires higher instantaneous injectivity than constant injection (as injection time is less), therefore, those earlier projects will be "easily" scalable when more volumes will be available, and more ships can be used to reduce shut-in times. If large volume pipeline will ever become a reality for the North Sea, the fleet of DSI ships can be used to bring CO_2 from the North Sea hub to new or more distant and dispersed storage locations.

3.4 Atlantic Coast of Portugal

3.4.1 Regional context

Policy and decarbonization framework

Portugal's decarbonization agenda follows four key policy frameworks: the National Energy and Climate Plan 2030 (PNEC 2030)[20], the Carbon Neutrality Roadmap 2050 (RNC2050)[21], the National Hydrogen Strategy (EN-H2)[22], and the Portuguese Climate Law (Law 98/2021)[23]. National Climate Law defines core emissions targets as at least 55% reduction by 2030, 65%–75% by 2040, and 90% by 2050,

[20] Revisão do PNEC 2030 PLANO NACIONAL ENERGIA E CLIMA 2021-2030 (PNEC 2030), pnec2030_para_aprov_ar.pdf

[21] LONG-TERM STRATEGY FOR CARBON NEUTRALITY OF THE PORTUGUESE ECONOMY BY 2050, roteiro_para_a_neutralidade_carbonica_2050_en.pdf

[22] Resolução do Conselho de Ministros n.º 63/2020, Diário da República, resolução-do-conselho-de-ministros-n-º-632020.pdf

[23] Lei n.º 98/2021, de 31 de dezembro (Lei de Bases do Clima), https://diariodarepublica.pt/dr/detalhe/lei/98-2021-176907481

all compared with 2005 levels. Additionally, amendments made in 2025 lays goal of carbon neutrality by 2045[24]. The revised 2024 PNEC 2030 recognizes CCUS as a necessary technology for hard-to-abate industries and as a way to achieve negative emissions through BECCS, with carbon neutrality set as the target by 2045. Beyond permanent geological storage, CO_2 utilization is also anticipated for hydrogen and synthetic fuel production.

Portugal has adopted the EU CCS Directive into national law through Decree-Law 60/2012, but a dedicated national CCUS strategy is still being developed. More importantly for this project, specific permitting rules for CO_2 shipping and ship-to-well injection have not yet been defined, which creates a regulatory gap directly relevant to DSI deployment.

CO_2 emitters and capture

As established in D3.1, 14 emitters out of an initial pool of 24 were found to be technically and economically suitable for CCS deployment (see Table 2). Together these emitters forecasts to ~9.36 Mt/yr of CO_2 available for capture, of which ~3.57 Mt/yr is fossil or process-based and ~5.79 Mt/yr is biogenic (mainly pulp and paper). Approximately 70% of biogenic emissions are accounted for CCS, and the remainder is directed for e-fuel production.

Table 2. List of emitters considered in the Atlantic coast of Portugal scenario and CO_2 emissions available for capture.

ID	EU ETS ID	Emitter Name	Cluster	Sector	Fossil+Process CO_2 $MtCO_2/yr$	Biogenic CO_2 $MtCO_2/yr$	CO_2 emissions $MtCO_2/yr$
1	196	Petrogal	Isolated emitter	Oil refining	0.72	0.12	0.84
2	291	Navigator Figueira	Figueira	Pulp & paper	0.02	1.21	1.24
3	277	Navigator Setúbal	Setúbal	Pulp & paper	0.02	1.12	1.14
4	48	CELBI Figueira	Figueira	Pulp & paper	0.00	1.54	1.54
5	145	Navigator Cacia	Isolated emitter	Pulp & paper	0.00	0.76	0.76
6	173	CIMPOR Alhandra	Lisbon	Cement	0.39	0.06	0.44
7	174	CIMPOR Souselas	Isolated emitter	Cement	0.40	0.05	0.45
8	102	SECIL Outão	Setúbal	Cement	0.67	0.12	0.79
9	103	SECIL Maceira-Liz	Leiria	Cement	0.34	0.07	0.41
10	-	Lipor	Isolated emitter	Waste to energy	0.21	0.21	0.41
11	-	Valorsul	Lisbon	Waste to energy	0.35	0.38	0.74
12	79	Lhoist	Leiria	Cement	0.29	0.12	0.42
13	202	CIMPOR Loulé	Isolated emitter	Cement	0.10	0.01	0.12
14	104	SECIL Pataias	Leiria	Cement	0.06	0.01	0.07
				Totals	**3.57**	**5.79**	**9.36**

CO_2 storage site

The primary CO_2 storage site is located in the northern Lusitanian Basin, approximately 22 km offshore from the port of Figueira da Foz, at relatively shallow water depths (~85 m at wellhead). The target formation structure Q4-TV1 is a smooth anticline within a deep saline aquifer (Torres Vedras / Figueira da Foz Group, Early Cretaceous; Figure 15), with a top-reservoir depth of 820–1,178 m below sea level and a reservoir thickness of approximately 340 m. Carbonates and marls of the Cacém (Costa de Arnes) formation provide the primary seal for the reservoir (see Figure 15**Error! Reference source not found.**). Static storage capacity assessments from the PilotSTRATEGY project indicate a most-likely capacity of ~251 Mt CO_2 with a conservative estimate of ~123 Mt and an optimistic estimate of ~421 Mt. The proximity of reservoir to shore (~22 km) favours the pipeline solution, but the shallow water depth is a significant positive factor for DSI.

[24] Resolution of the Assembly of the Republic No. 127/2025 of 10 April 2025, "Updating the National Energy and Climate Plan 2030," *Diário da República*, Series I, No. 71 (2025).

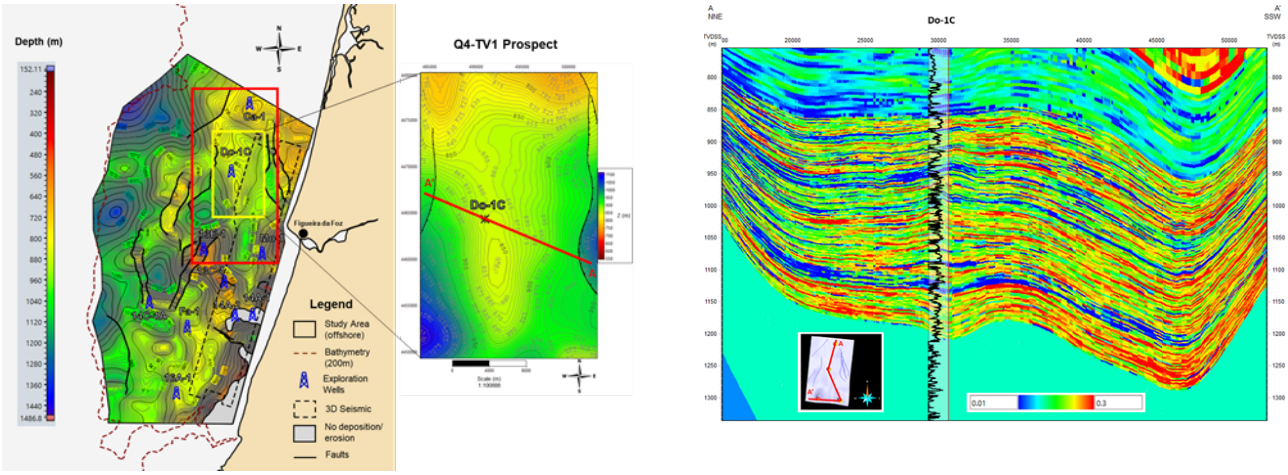


Figure 15. Left: Map of the top of the Torres Vedras Group reservoir structure illustrating the outlines of the study area of the 3D static model's boundary (red rectangle) and the reservoir model boundary covering the area of the Q4-TV1 prospect (yellow rectangle).

Transport configuration description

The base-case PIPE configuration connects all 14 emitters into a common onshore CO_2 pipeline system converging at Figueira da Foz, where it transitions to an offshore subsea pipeline connected to the Q4-TV1 reservoir.

The alternative DSI scenario retains pipeline transport for most emitters but adds ship-based transport with direct injection for sources near the ports of Sines and Setúbal, which are too distant from the storage. Figure 16 the complete schematic of these connection systems. In the DSI scenario, CO_2 at Sines port is the aggregation of emissions from the GALP refinery which is in the near vicinity of the port, and the Loulé cement plant Loulé which is situated 150 km south from the port. In the Setúbal cluster, the Navigator pulp and paper plant and the Outão cement plant are grouped together; both are in the vicinity of the port.

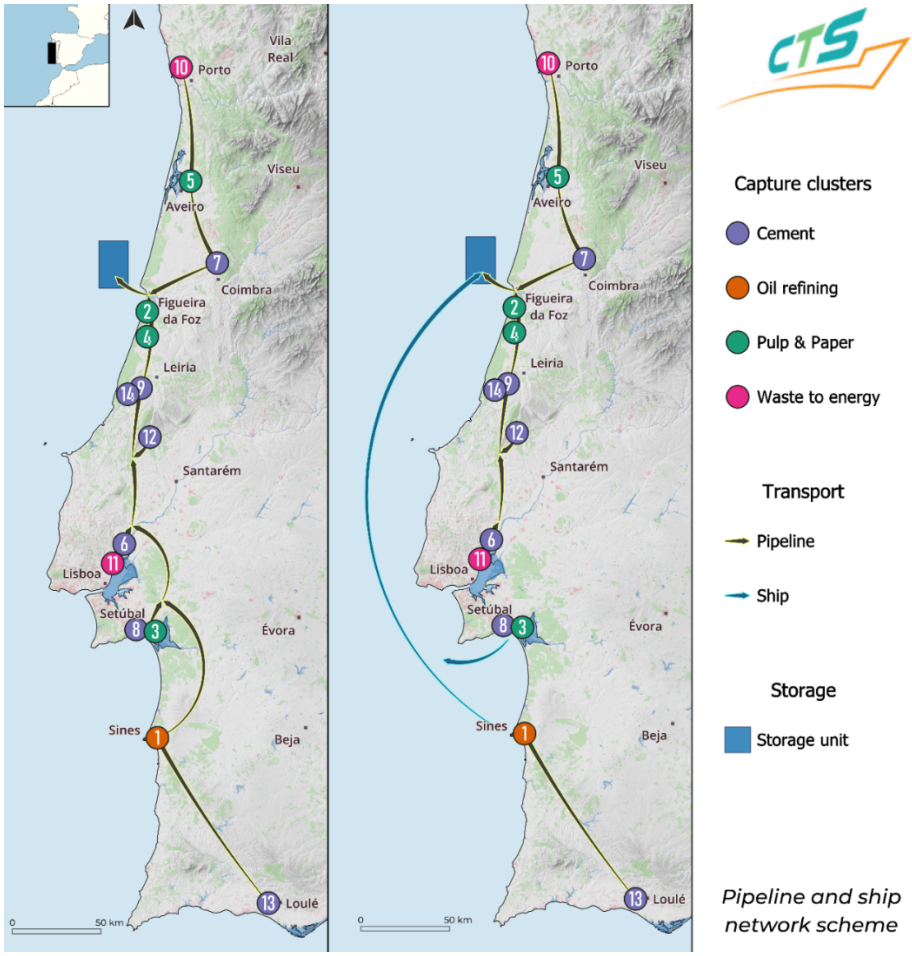


Figure 16. Left: Clusters and transport flow for PIPE scenario; Right: Clusters and transport flow for DSI scenario.

3.4.2 Main DSI drivers and opportunities

Regional response of categorized guiding questions for qualitative assessment for the Atlantic Coast of Portugal is represented in Figure 17as well as the colour code representing relevance of each question for the deployment of DSI in the region.

Guiding questions	Atlantic Coast of Portugal	
	Regional status	Regional relevance
Regulatory environment		
Regulations for CO2 transport by ship exists?	No	
Are ship permits faster than offshore pipelines?	Undefined	
Are absence of pipeline regulations an opportunity?	Undefined	
Environmental aspects		
Are noise impacts from ships an issue?	Yes	
Are pipelines and platforms a concern?	Yes	
Can potential CO2 leaks compromise habitats?	No	
Is direct injection an environmental concern?	Undefined	
Socio-economic impacts		
Are the visual impacts of platforms a concern?	Yes	
Are there possible conflicts with stakeholders?	Undefined	
Does direct injection favour job creation?	Yes	
Is there higher social acceptance for reversible solutions?	Undefined	
Technical feasibility		
Are the maritime conditions challenging?	Yes	
Are there long non-operational periods due to weather?	No	
Is there continuous supply of CO2	Yes	
Is continuous injection favoured by injectivity?	Yes	
Infrastructure & Logistics		
Do CO2 sources favour transport to a port?	Yes	
Are many small-scale CO2 sources identified?	No	
Is the platform technically justified for the expected capacity?	Yes	
Maturity & time-to-market		
Is rapid deployment needed?	Yes	
Is the pilot phase expected?	Yes	
Does direct injection accelerate deployment?	Yes	
Site-specific geological factors		
Is the reservoir injectivity suitable for intermittent injection?	Undefined	
Will initially only 1–2 wells be available?	No	
Is the storage site remote (e.g., deep water)?	No	

Figure 17. Regional status of guiding questions along with their relevance for Atlantic coast of Portugal (Colour code - Green: No relevance, Lime-green: Minor relevance, Yellow: Important relevance, Red: Critical relevance, double colour: possible lower relevance (left) with possible upper relevance (right)).

Figure 18 shows the cumulative relevance of each category for the Atlantic coast of Portugal across all classifications based on the scoring awarded in Figure 17. Solid bars show the baseline relevance scores, while hollow bars stacked on top reflect additional potential relevance where scoring ranges apply, capturing uncertainty between two scoring levels.

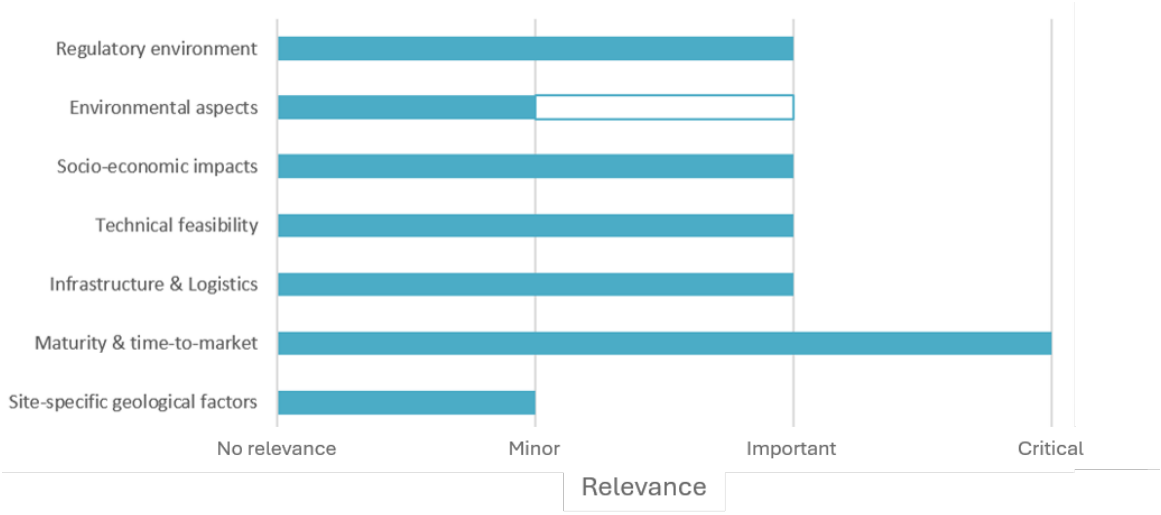


Figure 18. Cumulative relevance of each guiding category related to DSI implementation in the Atlantic Coast of Portugal region.

Maturity and time-to-market comes out as the highest-scoring categories, showing critical relevance for DSI. This reflects that it is **critical** for the DSI technology to advance rapidly in order for its potential value for the early deployment of CCS to become a reality. Regulatory environment, socio-economic impacts, technical feasibility, and infrastructure and logistics, all show important relevance, and that these dimensions are **important** but manageable with adequate permitting, stakeholder engagement, operational planning and port-side coordination. Site-specific geological factors and Environmental aspects score lower in comparison, i.e. **minor** or even **non-relevance** of these issues, which reflects the manageable site conditions and its relatively close proximity to shore in shallow waters.

The main drivers for DSI in the Atlantic Coast of Portugal are:

- **Regulatory framework:** Portugal currently has no operational CO_2 transport regulatory framework for any mode, pipeline or ship. While this is a barrier in the near term, it also means there are no pipeline centric assumptions built into existing national legislation. This opens the possibility of designing a transport permitting framework from the ground up that explicitly accommodates DSI operations, potentially making the approval process faster and more straightforward.
- **Flexibility and early deployment**: DSI allows CO_2 to be transported from multiple ports and injected into the reservoir without waiting for a complete pipeline network to be constructed. Given the national need to demonstrate storage capacity and meet EU ETS and national carbon neutrality targets, time-to-market is rated Critical, making this flexibility commercially and politically valuable.
- **Distance to storage site**: For the Sines and Setúbal clusters, whose distance from the storage site makes early pipeline construction difficult, DSI offers an early start, more flexible and scalable transport solution. Or until a fully integrated pipeline network becomes operational.
- **Licensing and administrative simplicity**: For the distant southern emitters, DSI avoids the administrative complexity that comes with building a pipeline network. Connecting these sources via pipeline would require construction approvals, adding significant overhead in time and effort. By removing this requirement, direct injection allows the project to move through a simpler regulatory process and can bring those sources closer to implementation sooner.
- The proximity of the storage site to shore (~22 km) and its shallow water depth (~85 m at wellhead) provide an opportunity for discarding a permanent offshore platform. This is a

notable advantage, as offshore platforms are not only capital-intensive but can also create visual and environmental concerns for coastal communities and tourism.

- **Job creation:** Implementing DSI would create and/or sustain jobs in port operations, shipping, vessel services and subsea engineering in Figueira da Foz, Sines and Setúbal. This would reinforce the local economy, a relevant factor for the technological solution.

3.4.3 Main DSI barriers and risks

Despite the strong case for DSI in early phases, several significant barriers and risks are identified:

- **CO_2 supply and spatial distribution of sources**: The continuous availability of CO_2 volumes and the spatial distribution of emitters are highlighted as critical barriers that may hinder DSI. While DSI can operate in batch mode, reservoir management and ship scheduling are generally more efficient with continuous or near-continuous injection. This can disrupt CO_2 availability and require large intermediate buffer storage and complicated scheduling making DSI less efficient and cost intensive.
- A significant share of the CO_2 in the Setúbal cluster is biogenic, meaning DSI could allow pulp and paper sources from Setúbal to contribute to negative emissions if stored, directly supporting Portugal's BECCS targets under PNEC 2030 and RNC 2050. While DSI offers initial flexibility for these sources, the associated higher CAPEX and OPEX makes it more expensive in the long run, compared to a fully utilized regional pipeline.
- **Regulatory framework**: No dedicated national framework currently governs CO_2 transport by ship or DSI in Portugal. While international instruments like OSPAR[25] are progressively addressing frameworks, the timeline for integration into Portuguese law and the distribution of responsibilities between national authorities remains unclear. Until a clear and DSI-specific permitting pathway is established, project developers may face delays that reduce the attractiveness of DSI relative to pipeline.
- **Environmental aspects**: the selected injection site is within environmental protected areas, subject to EIA requirements. Noise from DP vessels and the risk of accidental CO_2 releases during operation, connection and disconnection are primary concerns that need to be addressed at EIA level.
- **Socio-economic impacts**: the fishing sector and coastal tourism communities at Figueira da Foz are both sensitive stakeholders. While the absence of offshore platform removes one source of visual conflict, both for the PIPE and DSI scenarios, CO_2 injection operations as competing with or threatening traditional fishing grounds is a concern that needs to be addressed. Restrictions to fishing activities, maritime navigation and recreational maritime activities imposed by having vessels almost continuously operating over the injection site may also raise social acceptance issues.
- **Metocean conditions**: The Atlantic coast of Portugal experiences severe winter storms that affect ship operability and injection continuity. Modern DP vessels are generally capable of holding position and continuing operations through most weather conditions, but extended storm periods can disrupt CO_2 supply, complicate injection scheduling, and introduce operational risks during connection and disconnection at the wellhead.

[25] Frattini, L., Becattini, V., Mazzotti, M., Main current legal and regulatory frameworks for carbon dioxide capture, transport, and storage in the European Economic Area. International Journal of Greenhouse Gas Control, 136, 104172, July 2024. https://doi.org/10.1016/j.ijggc.2024.104172

3.4.4 Regional recommendations

Given the drivers and barriers identified, the following recommendations are proposed to manage risks and build replicability of DSI utilisation in possible scenarios for CCS deployment in Portugal:

Regulatory and Policy:

1. It is likely that the regulatory framework for CO_2 transport is addressed at EU level, since the European Commission is working on a regulation. Unlike Directives, which must be translated into the national law, EU regulations are brought immediately into effect in Member States. Thus, Portugal would directly adopt the EU regulations for CO_2 transport as they come into force, which removes the need for a standalone national framework. Therefore, continuous monitoring of the evolving transport regulatory framework is important. Engaging with relevant competent authorities and stakeholders would further enable the anticipation of compliance requirements.

Environmental Aspects:

2. Given that the storage site lies within an environmental protected area, an EIA is required by law. The EIA should specifically address noise generated by DP vessels as this is a known concern for marine mammals in the area and is likely to require dedicated monitoring protocols and potentially vessel-specific mitigation measures.
3. The possibility of the creation of a protection zone around the injection site could act as a marine sanctuary, creating an environmental co-benefit, should be the target of an ecological assessment.

Socio-Economic Impacts

4. The regular presence of CO_2 carriers over the injection site, is a legitimate concern for recreational and commercial navigation, and continuous engagement with operators and local municipalities should begin early.
5. Direct dialogue with fishing communities, which may feel affected in their activities, and regulatory authorities is equally important. A clear communication strategy explaining operations and strategy, alongside the employment benefits for the region, will be key to maintaining broad social acceptance.

Stakeholder engagement

6. Environmental and socio-economic issues impose a stakeholder engagement strategy that should start during EIA scoping and continue through pilot operation. The plan should cover fisheries, tourism, navigation users, municipalities, port authorities and environmental NGOs. This should be done using regular briefings, published exclusion-zone maps, vessel schedules, and a grievance channel.

Metocean conditions

7. Modern DP vessels are expected to keep disruptions within manageable limits for most of the year. Intermediate buffer storage will help to maintain injection continuity, although adverse weather periods may prevent the vessels from operating, imposing shutdowns of the injection system. Buffer storage will absorb supply variability without forcing capture shutdowns when offshore transport is infeasible because of weather conditions, but the costs associated are high and economic feasibility must be carefully considered.

8. Contingency plans for safe disconnection and re-connection under storm conditions should be developed early and built into the operational design from the outset.

Maturity and time-to-market

9. Due to national climate commitments and EU ETS compliance pressure, rapid development in Portugal is critical, making it essential that policy and permitting barriers are addressed without delay. A pilot project is both expected and necessary, not only to demonstrate storage capacity but to validate the site under real injection conditions before any commercial-scale operations. DSI is particularly well-positioned in this context because of its flexibility and early deployment. However, DSI is not yet fully mature. While the Greensand project in Denmark is developing and testing key elements of ship-based CO_2 injection, a complete DSI solution still requires pilot-scale demonstration. Thus, further technological development of the DSI solution and a techno-economic demonstration of its feasibility should be developed as part of testing the reservoir capabilities in a pilot project, so that the technology reaches a TRL 8-9 before 2030.

Transitioning early-stage option

10. Given the expected CO_2 supply profile, the spatial distribution of sources, and the results of the TEA presented in D3.1 (Mesquita et al, 2026), a pipeline-based network is likely to become more economically robust once sufficient volumes are aggregated. However, if the maturity and time-to-market issues of DSI are solved, DSI feasibility should be assessed as a transitional option, rather than as Portugal's default long-term CO_2 transport solution. Its flexibility can accelerate the start of the Portuguese transport network, connect distant emitters such as Sines and Setúbal, and support storage demonstration before full-scale pipeline infrastructure is justified.

4 Opportunities for DSI in the Mediterranean

4.1 Introduction

This section aims to understand the applicability of DSI for the development of CCS in the Mediterranean region. Accordingly, only the offshore transportation section and related infrastructure are assessed in the CCS chain. Common infrastructure, such as onshore infrastructure costs up to the ports, storage-specific costs like well drilling and subsea CO_2 distribution components, are not included, which gives a pure optimization and comparison of the transport mode. The assessment covers Spain, Morocco, Egypt, France, Italy, and Greece, together with the offshore storage options of Ebro, Ravenna, and Prinos. For each country all the possible hub ports were considered and narrowed down to the most appropriate port.

Transport mode cannot be selected independently of the rest of the network, with its cost depending on which ports it connects and how flow is subsequently distributed between storage sites[26]. The mass split between storage sites is optimized independently for each combination to obtain its minimum-cost outcome. Results are expressed as relative cost, normalized Present Value (nPV), against the lowest-cost scenario, consistent with the comparative approach used in other CCS network studies, and by testing the full combination space rather than a limited set of predefined routes.

[26] V. Becattini et al., "Carbon dioxide capture, transport and storage supply chains: Optimal economic and environmental performance of infrastructure rollout," Int. J. Greenh. Gas Control, vol. 117, p. 103635, Jun. 2022, doi: 10.1016/j.ijggc.2022.103635.

4.2 Overview of CO_2 sources and sinks in the Mediterranean

4.2.1 Regional scope (countries and emitters)

The selection of countries and emitters is based on the framework developed in the CCUS ZEN project [27, 28] for the European Mediterranean region. The list of countries adapted from CCUS ZEN is updated to include Greece, Egypt and Morocco. The final scope of countries includes Spain, France, Italy, Greece, Egypt, and Morocco.

The selection of emitters includes hard-to-abate sectors such as power generation, refining, cement, steel, non-iron metals and chemicals. Selection is based on recorded emissions, sector-specific reduction factors representing future decarbonization, and a minimum threshold of 0.1 Mt/yr per emitter. Additional country-specific screening constraints are applied where required to preserve geographical coherence and comparability across the regional configurations which are defined in Section 4.3 & 4.4. Figure 19 represents the geographical locations of these emitters prior to the screening. The figure excludes emitters from Egypt as a different selection criterion is considered.

Following emitter screening, national CO_2 flows are aggregated at one selected hub port per country for the comparative runs, while Spain and Italy retain multiple candidate hub options during scenario testing. This allows port choice to be assessed jointly with reservoir allocation and transport mode selection. Aggregated CO_2 at the hub port is then transferred and injected into a reservoir using one of three distinct transportation modes as compared: conventional ship with platform (SHIP), direct injection ship (DSI) and pipeline (PIPE).

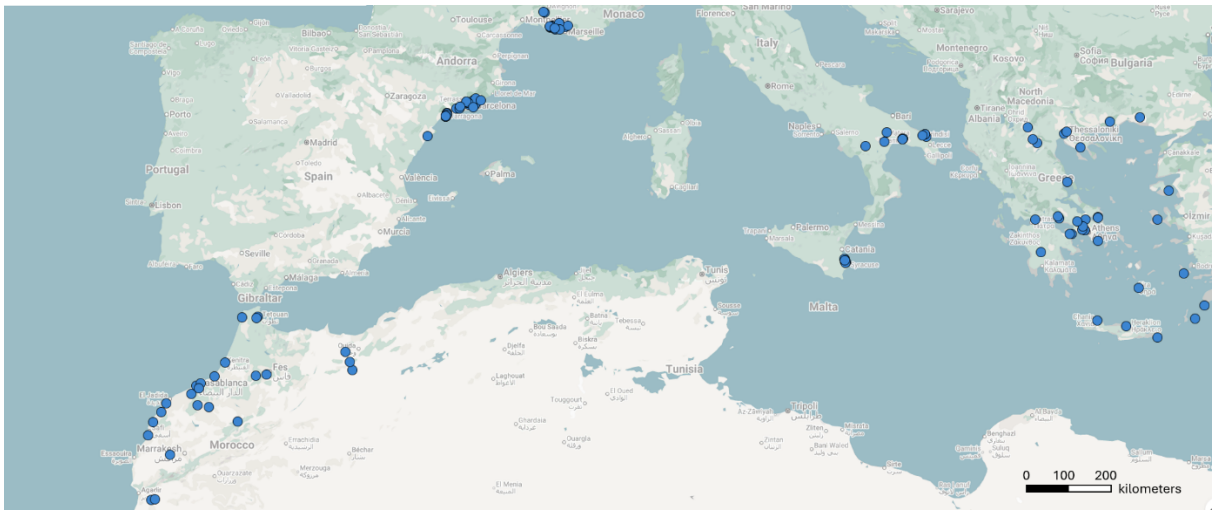


Figure 19. Geographical location of major CO_2 emitters of all the selected countries (except Egypt) as per the framework (Author creation and Gravaud, I. et al. (2023) [29])

4.2.2 Offshore CO_2 reservoirs

Three offshore reservoirs are considered, Ebro offshore Spain, Ravenna in the Adriatic Sea, and Prinos in the northern Aegean Sea, following on the CCUS ZEN project. Together, these provide representative

[27] A. Shogenova et al., "D3.1 CCUS value chains for the two CCUS ZEN regions selected for further development in WP4," 2024, Zenodo. doi: 10.5281/ZENODO.17864912.

[28] C. Ringstad et al., "D1.1 High-level regional mapping of CO2 emission sources, utilization industry and infrastructure in the Baltic Sea and Mediterranean Sea regions," Jun. 2023, Zenodo. doi: 10.5281/zenodo.14392847.

[29] Gravaud, I. et al. (2023) D1.2 Identification of promising CCUS value chains in the two ZEN regions for further analyses in WP3. Zenodo. Available at: https://doi.org/10.5281/zenodo.14393008.

storage options across the considered western, central, and eastern Mediterranean countries. Each reservoir has different characteristics and storage capacities:

- Ebro reservoir basin: It is located off the coast of Tarragona in Spain with an estimated CO_2 storage capacity of 200 Mt[30]. Reservoir is in the upper Miocene Castellón Sandstones, which runs from approximately 1600 m to 1900 m deep, overlain by the Ebro clays (Pliocene). Studies such as those in projects PilotSTRATEGY and Strategy CCUS has been conducted to evaluate the viability of this reservoir with positive outcomes and an expected pilot in the near future. In this deliverable, this reservoir is assessed to be shared between multiple countries namely, Spain, France, Morocco and Italy.
- Ravenna reservoir: This reservoir is located off the coast of Ravenna in Italy with an estimated CO_2 storage capacity of 500+ Mt[31]. It is a depleted natural gas reservoir beneath the Adriatic Sea, located at a depth of more than 2,500-3,000 m below the seabed. ENI and SNAM are already developing the project with the aim of achieving an annual injection capacity of 16+ Mt per annum. In this deliverable, this reservoir is assessed to be shared between France, Italy and Greece.
- Prinos reservoir: It is a saline aquifer reservoir located in the Gulf of Kavala, about 2.4 km east of Nea Karvali in the northern Aegean. It lies at the depths of 1900-4200 m[32] in the Prinos complex. EnEarth, an Energean subsidiary, is developing the Prinos CO_2 Storage Project by repurposing existing oil and gas infrastructure and constructing additional onshore and offshore facilities. The ongoing EnEarth Prinos project targets a structure with a total storage capacity of approximately 66 Mt[33],whereas the gross total estimated CO_2 storage capacity of the reservoir complex is 1000 Mt[34, 35]. Therefore, and for consistency with the approach in CCUS ZEN, the latter capacity of 1000Mt is used for this storage site, thus assuming that further structures are available, more than that of the current EnEarth project.

Each country hub and reservoir connection option is assessed for only selected transport modes, meaning not all three transport modes are available for all the connections. These options are further defined in individual country description in Section 4.4.

4.3 Underlying Structure of the Quantitative Model

This section firstly describes the methodology used to screen the emitters and country hub ports to narrow down the scope of study to viable options. This is followed by a description of the simulation model used in MATLAB - SIMULINK to get the most optimized solution for the Mediterranean CCS under study.

[30] Isaline Gravaud, Audrey Lopez, Ioannis Koumentis, Saif Sleiman, Laurianne Bouvier, et al. Developing CCUS in Mediterranean Region–Technical Evaluation of Promising Value Chains. 17thInternationalConferenceon Greenhouse Gas Control Technologies, GHGT-17, Oct 2024, Calgary, Canada. ⟨10.2139/ssrn.5068514⟩.

[31] CCS Eni-Snam: Ravenna Hub.

[32] 8a-environmental-impact-assessment-ειά-phase-1-key-annexes.pdf

[33] Energean. *Prinos CO2*. Retrieved August 24, 2026, from https://www.energean.com/operations/greece/prinos-co2/

[34] Shogenov, K. et. al. (2024) A framework for the selection of promising CCUS value chains in the Baltic and Mediterranean regions, CCUSZEN, https://www.ccuszen.eu/sites/default/files/Webinar%204%20slides.pdf (Accessed on: 24 July 2026)

[35] GSEU Project (2025). Map of CO2 storage potential areas (formation, units and traps) at the EU-scale. Version 1.0. Access information on April 1st, 2025 [https://www.europe-geology.eu/data-tools/map-viewer/].

4.3.1 Transport modes

As defined in this deliverable, three modes of transport are assessed. For simulation purposes, these modes are indexed in this study as shown in Table 3. To enable comparative analysis of both ship modes of transportation, ships are sized with the transport capacity of 50,000 t CO_2.

Table 3. Transport mode abbreviation and index used.

Transport mode	Abbreviation	Mode (m) index
Conventional Ship	SHIP	1
Direct Injection Ship	DSI	2
Pipeline	PIPE	3

4.3.2 Emitter and port selection

CCUS ZEN project reports are used as the starting point to get the reported emissions from the selected countries. The project reports cover France, Italy, Turkey, Greece and Spain in the Mediterranean. Emitters from France, Italy, Greece and Spain are procured from the CCUS ZEN with validations carried out using EU ETS and E-PRTR databases. Morocco does not fall under EU ETS[36] and/or E-PRTR[37] and does not have national emitter level emission database yet. Therefore, Climate TRACE inventory[38] dataset is used to get the emitters data in hard to abate sectors. Similarly, Egypt does not yet have nationalized emitter level database, therefore a different approach is applied, which compares the DSI and SHIP solution by considering how much each vessel) can carry in a year. Considered emitters are mapped as in Figure 19.

Emission from industries (specifically non-biogenic emissions) are expected to reduce in the future. This reduction is driven by energy efficiency increase in the industries, switchover to more sustainable and renewable fuels, upgrades to more efficient technologies for energy production like hybrids, electrification, etc. These changes are not uniform across industries as each industry follows has its own roadmap, therefore, each industry needs to be assessed differently. To estimate the results closer to more realistic values, these emission forecasts are done for each country industry wise. Complete path followed is detailed in Annex C.

A two-stage screening process is followed while selecting the hub port:

- In the first stage, port infrastructure capacity is assessed, highlighting infrastructure maturity and operational readiness for potential DSI deployment.
- The second stage varies by country and reflects differences in geographic context. For France, the second-stage criterion is proximity to candidate offshore storage reservoirs. For Greece, Morocco, and Egypt, port selection is driven by country-specific logistical constraints related to emitter locations. For Spain and Italy, where multiple suitable ports are assessed, the optimization model is repeated for all possible port combinations. The combination that yields the lowest minimum lifetime discounted cost, as defined by the objective function, across all simulation runs is then selected as the final hub assignment for both countries.

4.3.3 Simulation model and scenario optimization

The model is developed in MATLAB and SIMULINK to evaluate all the possible configurations of transport modes in each hub port and reservoir connections with the optimization of mass flow splits where more than two reservoir options are present for a country. Additionally, the complete model

[36] European Environment Agency, "EU Emissions Trading System (EU ETS) facility-level emission data." [Online]. Available: https://union-registry-data.ec.europa.eu/report/welcome

[37] Dataset | Industrial Emissions European Industrial Emissions Portal

[38] "Climate TRACE (2026), Climate TRACE Emissions Inventory v5.3.0." Available: https://climatetrace.org

simulation is executed repeatedly to cover all the possible Italian and Spanish port combinations to find out the best-suited hub port for both countries.

Overall, the model in each scenario covers a specific mode of transport per country-reservoir while optimizing the mass distribution for countries with more than one storage options are available. This optimization and scenario simulation strategy is summarized in Figure 20.

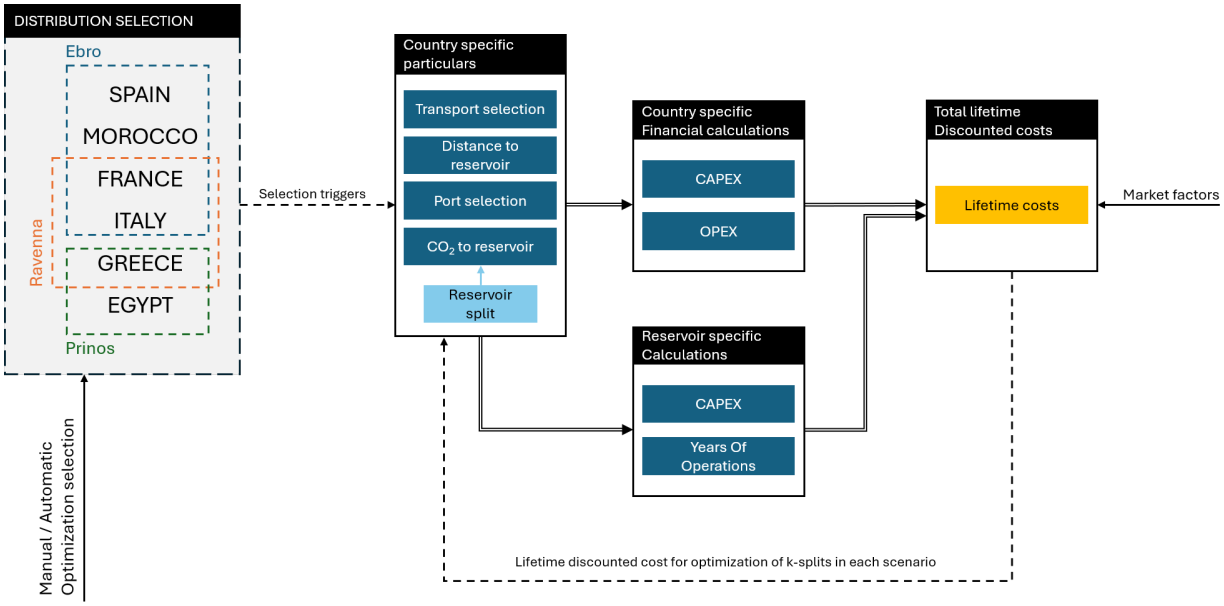


Figure 20. Overview of MATLAB/Simulink model workflow for transport selection, cost calculation, and lifetime discounted cost optimization.

Overall, the model is divided into three parts as depicted in Figure 20. First part**, Distribution and country particulars**, establishes physical parameters like hub ports, distances, national CO_2 to be stored, CO_2 mass splits to reservoirs (wherever applicable) and transport mode selections. Second part, **Financial Calculations**, performs financial CAPEX and OPEX calculations at country and reservoir level individually. Lastly, **Lifetime Discounted Costs** part, adds all the discounted CAPEX and OPEX values and estimates the lifetime costs. The model minimizes the objective function (lifetime discounted costs) in each scenario to optimize the mass split and retrieves the optimized lifetime cost of the complete scenario.

Annex B provides the detailed screening assumptions, model formulation, financial parameters, optimisation procedure and equations.

4.4 Configuration descriptions

This section defines the national emissions after applying the decarbonization factor and screening emitters against the minimum threshold for the common CCUS ZEN countries and other countries under consideration. It also identifies the available storage options for each country and presents the transport modes studied, along with the distances for each hub-to-reservoir connection.

4.4.1 Spain

With screening methods applied over emitters mapped in CCUS ZEN, the cement sector accounts for 36% of 4.2 Mt/yr Spain's total national industrial emissions. Barcelona (BAR), Valencia (VAL) and Algeciras (ALG) are the three major Mediterranean Spanish ports where, Barcelona and Valencia are comparatively close to each other and Algeciras lies in the southernmost part of the country. All three

ports have recently received investments and are boosting their infrastructures, therefore, all three ports are considered for comparison[39].

The Ebro reservoir lies within its Exclusive Economic Zone of Spain and it is the obvious choice of the country for CO_2 storage. Distance to the reservoir is 132 km, 180 km and 880 km from BAR, VAL and ALG, respectively. For all the possible connections, all the transport modes, CS, DSI and pipeline are assessed.

4.4.2 Morocco

Morocco does not have an EU ETS like emitter level database yet. Therefore, publicly available CLIMATE Trace dataset is used for the approximate emitter level emissions. Cement and power generation together account for most of Morocco's industrial emissions, with the power sector alone representing 93% of the estimated 1.5 Mt/yr.

Morocco is closest to offshore Ebro reservoir and only Ebro is considered as the designated storage unit. For hub port selection, proximity to the reservoir is considered, narrowing down the list from to Nador. The resultant distance between hub and reservoir is 750 km with CS and DSI possible mode of transport for analysis.

4.4.3 France

The CO2 emissions available for storage from SE France, as considered in CCUS ZEN and this study, are estimated at 6.0 Mt/yr, where Iron & Steel with 29% is the major contributor. Marseille Fos, the largest Mediterranean port in France is considered as the hub to carry the national emission to the reservoir(s).

Offshore Ebro, in Spain, and Ravenna reservoir, in Italy, both are considered as possible storage sites for these sources and therefore, mass split optimization along with transport mode is analysed for both connections. In case of offshore Ebro, all three transport modes are assessed and compared for the connection distance of 500 km, whereas the 2200 km Marseille Fos-Ravenna connection considers CS and DSI only.

4.4.4 Italy

A total of 11.7 Mt/yr of CO_2 emissions from sources in Southern Italy and Sicily were estimated for capture under the screening methodology, with 53% originating from the power sector alone. Genoa (GEN) in the north and Gioia Tauro (GIA) in the south are identified as hub ports for transporting CO_2 and represents distinct case to find out best hub port.

The CO_2 is distributed between two storage sites, offshore Ebro and Ravenna. From Genoa and Gioia Tauro, the transport distances are 760 km and 1500 km to offshore Ebro, and 2000 km and 1200 km to Ravenna, respectively. In all the simulated connections from Italy, only CS and DSI is considered for comparison.

4.4.5 Greece

The EU ETS database is used to map Greece's industrial emission landscape. In addition to applying the CO_2 estimation methodology, the analysis is limited to emitters located near Athens. This geographic restriction is justified because emitters are dispersed across numerous islands; focusing on the major hub port of Piraeus (Athens) reduces the complexity of the pre-port transportation chain. After

[39] O. Oulmakki, J.-P. Rodrigue, A. Hernandez Meza, and J. Verny, "The implications of Chinese investments on Mediterranean trade and maritime hubs," *J. Shipp. Trade*, vol. 8, no. 1, p. 28, Nov. 2023, doi: 10.1186/s41072-023-00157-6

screening and reduction, total emissions are estimated at 4.9 Mt CO_2 per year, with refinery emissions accounting for the largest share at 59%.

Two reservoir connections, Piraeus-Ravenna and Piraeus-Prinos with distances of 1500 km and 410 km are considered, respectively. The optimization of mass split is also done between these reservoirs in each simulated scenario. All the three transport methods for Piraeus-Ravenna and both ships transport modes for Piraeus-Prinos are analysed within each scenario.

4.4.6 Egypt

Similar to Morocco, Egypt does not have an active, public, facility-level emissions database like EU ETS and therefore, CLIMATE Trace dataset is used for approximate identification of emitter level CO_2 emissions. 100 initial emitters were identified from the dataset and out these, 89 passes screening methodology. The number of sources and resulting volumes of CO_2 was too high to assess in this high-level approach. Therefore to compare only the considered transport modes, SHIP and DSI from Egypt, an amount ofCO_2 equal to what the defined ship can carry (0.99 Mt/yr) is considered from the port of Port Said. It reduces complexity and focuses on comparison of technology with the distance of 1300 km to the designated reservoir, Prinos.

Figure 21 represents the common transport paths of all six countries and reservoirs connection combinations as discussed in this section together and Table B.1 records all the Key Distribution parameters of these connection combinations. Lastly, Figure 22 represents the geographical location of all the selected emitters (except for Egypt).



Figure 21. Common transport modes paths assessed by each possible country hub port and reservoir studied.

Table 4. Considered national emissions, hub ports-reservoir connections, distances and transport modes for all six studied countries.

Country	Estimated emissions [Mt/yr]	Considered hub ports	Reservoirs	Distance to reservoir [km]	Considered transport modes	Connection
Spain	4.2	Barcelona/Valencia /Algeciras	Offshore Ebro	132/180/880	CS + DSI + Pipeline	C_1
Morocco	1.5	Nador	Offshore Ebro	750	CS + DSI	C_2
France	6.0	Marseille Fos	Offshore Ebro	500	CS + DSI + Pipeline	C_3
			Ravenna	2200	CS + DSI	C_4
Italy	11.7	Genoa/Gioa Tauro	Offshore Ebro	760/1500	CS + DSI	C_5
			Ravenna	2000/1200	CS + DSI	C_6
Greece	4.9	Piraeus	Ravenna	1500	CS + DSI + Pipeline	C_7
			Prinos	410	CS + DSI	C_8
Egypt	0.99	Port Said	Prinos	1300	CS + DSI	C_9

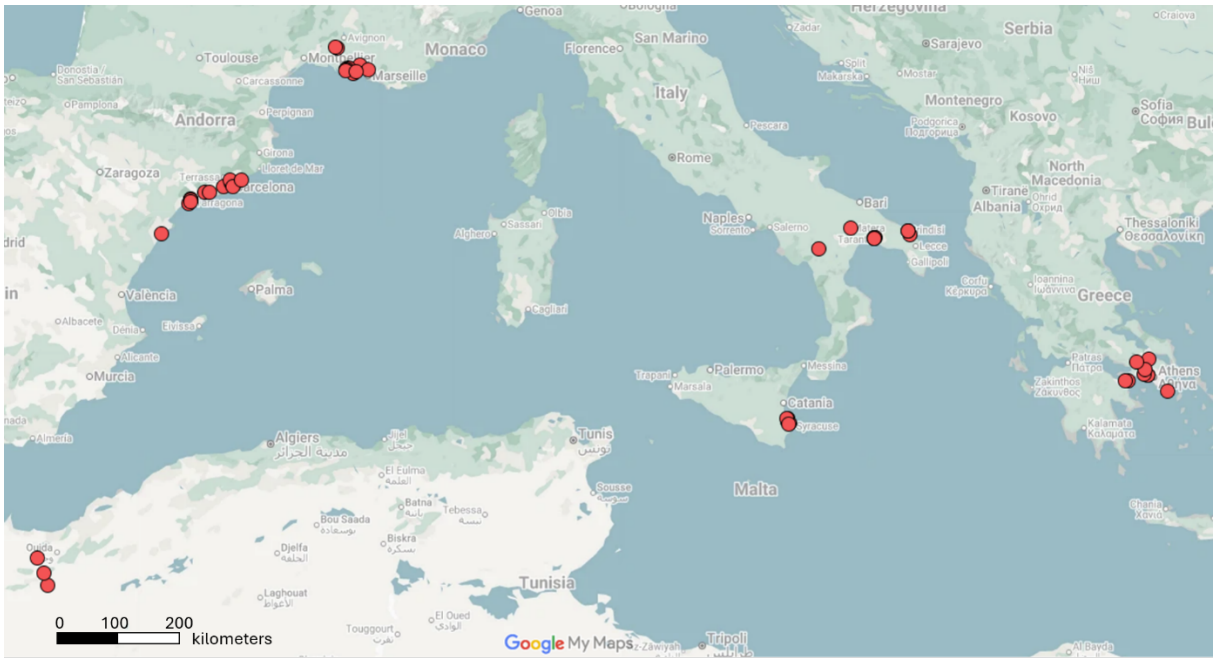


Figure 22. Geographical locations of all the selected emitters after screening process of all the countries considered in the study (except for Egypt).

4.5 Results and discussion

Three out of six countries have two storage options making a total of nine connection combinations. Each connection either has three or two transport options as seen in

Table 4, this makes total combinations of possible scenarios in each case equal to 1,728. Additionally, the model finds the best port for Spain and Italy where, Spain has three hub ports options and Italy has two. This makes 6 possible Spain-Italy hub combinations, creating a global scenario pool and bringing total scenario counts to 10,368. This covers all the possible available transport for each connection and combinations with optimized mass splits for France, Italy and Greece.

The output of each scenario, its objective function – the discounted lifetime cost, is normalized to allow for effective comparison of all the scenarios. The normalized objective function or normalized present value (nPV) is the ratio of each scenario's output to the minimum output across all 10,368 scenarios. This clearly represents the increase and relative economic penalty for using different transport modes for any considered connection and combination with respect to the best scenario.

The global minimum (nPV = 1) occurs with the Barcelona and Genoa as the hub ports for Spain and Italy where pipeline is used between Barcelona and Ebro connection and SHIP for every other connection. Minimum scenarios of all six cases are summarized in Table 5 showing the transport modes for each connection, CO_2 mass split factors for France, Italy and Greece along with calculated normalized present Value. Most optimum scenario with Barcelona and Genoa as the hub ports for Spain and Italy respectively is depicted in the Figure 23 that shows the transport route and selected mode of transport between port and reservoir.

Table 5. Best-case transport mode selection and normalized PV for each of the six Spain–Italy port combinations.

Spain	Italy	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	***nPV***
BAR	GEN	PIPE	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	1.000
VAL	GEN	PIPE	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	1.017
BAR	GIA	PIPE	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	1.051
VAL	GIA	PIPE	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	1.067
ALG	GEN	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	1.165
ALG	GIA	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	SHIP	1.237

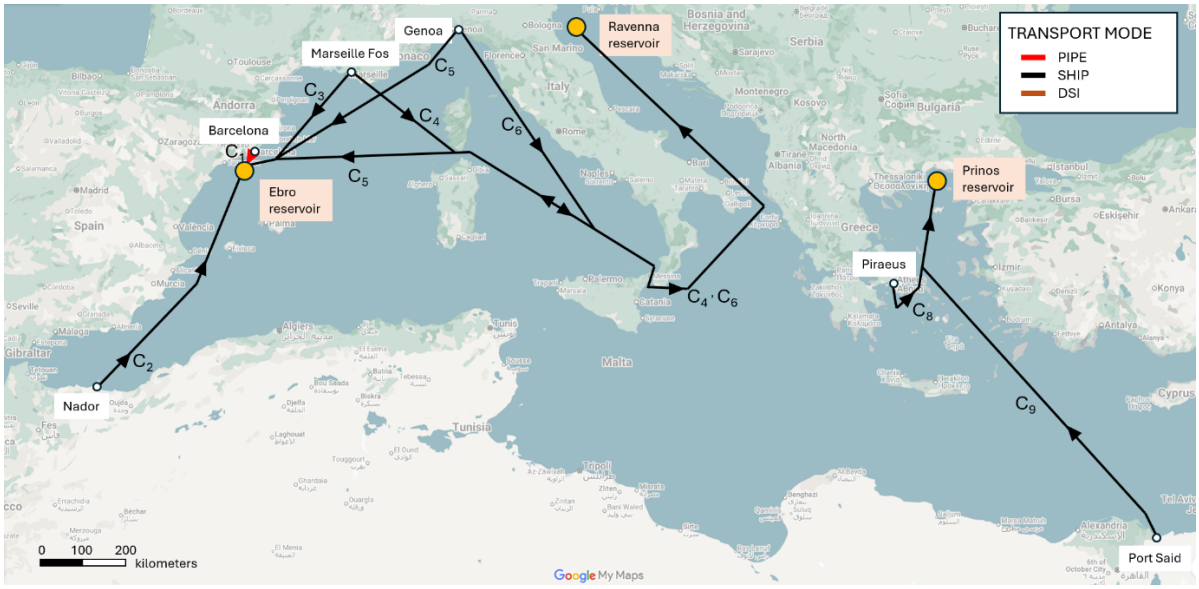


Figure 23. Resulted most optimum configuration of mode of transport and hub ports for each connection.

The difference between the top two scenarios in Table 5 is only 1.7%, and both use the same transport configuration and mass splits. In the global scenario pool, BAR-GEN appears once more with an nPV of 1.016, representing a 1.6% increase, but with a different transport configuration. All transport combinations remain identical to those of the nPV = 1.00 scenario, except for the France–Ravenna

connection (C_4) where DSI makes a viable option. At the full CCS-chain scale, this difference becomes almost negligible, indicating that DSI may be a feasible option for this connection and worth studying in detail.

Figure 24 shows the DSI selection rate for each connection as the percentage difference in nPV from the global minimum increases. As the percentage increases, more scenarios are included, towards the end, every simulated combination for each connection is included (all 10,368 scenarios). At that point, the DSI selection rate stabilizes according to how many transport modes that connection has. For example, if a connection has three transport options, the long-run frequency of any one solution (including DSI) tends toward 1/3 (≈33.33%), if there are two solutions, it tends toward 1/2 (50%).

The DSI selection rate at lower difference percentages can be used to identify the connections for which DSI is a competitive solution. Within a 10% cost difference from the global minimum nPV, 169 scenarios exist. In these scenarios, DSI presents a competitive mode of transportation for various connections. Connections France-Ravenna (C_4), Greece-Ravenna (C_7), Egypt-Prinos (C_9), Italy-Ravenna (C_6) and Morocco-Ebro (C_2) exhibit DSI as a competitive solution with DSI selection rates of 47%, 43%, 38%, 30%, and 30%, respectively.

Figure 25 shows these results within 10% cost difference band.

While connection C_3 (France-Ebro) and C_5 (Italy-Ebro) have very low DSI selection rates within the specified range, C_1 (Spain-Ebro) does not appear until 22% nPV cost difference. This indicates that DSI is not an optimum solution for Spain-Ebro connection. Up to a 12.4% difference, PIPE is the only solution for C_1, and only Barcelona and Valencia options appear within this range for Spanish port selection. This result is consistent with the literature[40, 41], which identifies PIPE as the most cost-effective transport option over short distances, because the distances from the Spanish ports of Barcelona and Valencia to the reservoir are relatively short.

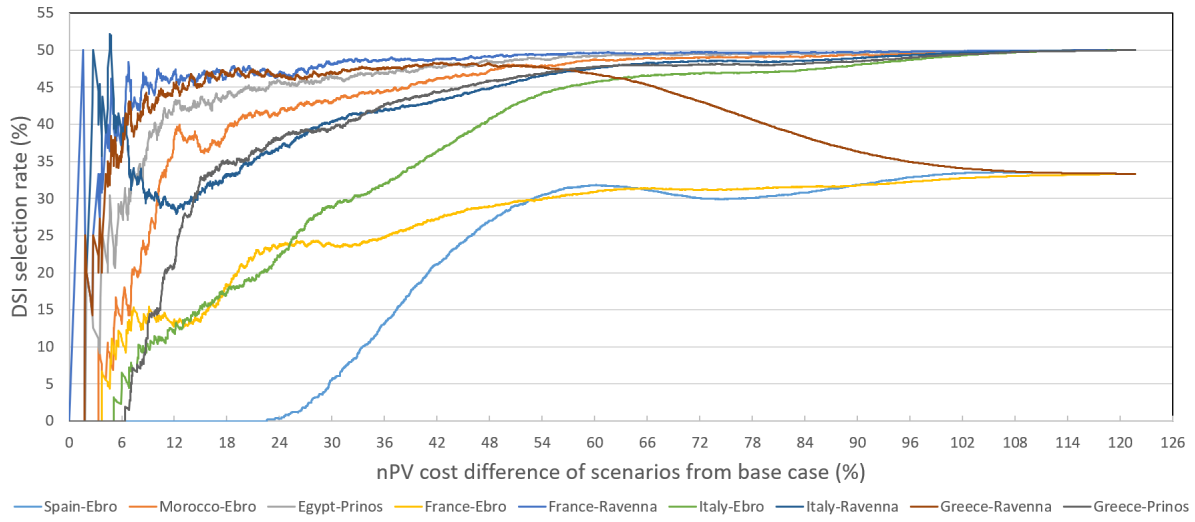


Figure 24. Number of times DSI as the mode of transportation is selected in all the 9 connections in percentage vs increase in nPV cost difference with respect to global minimum nPV.

[40] Nogueira, T., Rochedo, P. R. R., & Szklo, A. (2022). Evaluation of offshore CO_2 transport alternatives in Brazil. *International Journal of Greenhouse Gas Control, 116*, 103629. https://doi.org/10.1016/j.ijggc.2022.103629

[41] Knoope, M. M. J., Ramírez, A., & Faaij, A. P. C. (2015). Investing in CO_2 transport infrastructure under uncertainty: A comparison between ships and pipelines. *International Journal of Greenhouse Gas Control, 41*, 174–193. https://doi.org/10.1016/j.ijggc.2015.07.013

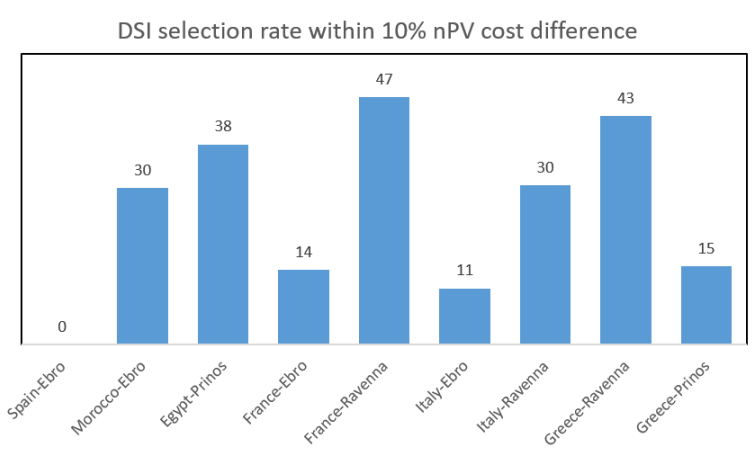


Figure 25. Percentage of times DSI occurs as the selected mode of transportation for each connection within the nPV cost difference of 10% w.r.t. global minimum nPV

The scenario analysis for connections where a mass split between reservoirs is available is, in some cases, dependent on the transport mode selected. This mass split, represented by k_{FR}, k_{IT} and k_{GR}, allocates the fraction of national CO_2 mass between the two reservoirs available to France, Italy and Greece respectively. A value of 1 for k_{FR} or k_{IT} means that 100% of the national mass is allocated to Ebro, with other option being Ravenna. For k_{FR}, a value of 1 means 100% of the mass is allocated to Ravenna, with other option being Prinos. The mass split can take any value between 0 and 1, since the scenario optimization determines the split freely rather than forcing an all-or-nothing.

The analysis shows that k_{FR} attains a value of 1 in 60% of scenarios, and k_{GR} attains a value of 0 in 88% of scenarios, meaning that in these cases, all of the CO_2 mass flows to Ebro (for France) and to Prinos (for Greece). This indicates that these two connections are not strongly sensitive to hub port configuration or transport mode selection. k_{IT}, on the other hand, does not replicate this behaviour, its mass split is spread across the full range between 0 and 1 with no dominant value. This indicates that the Italian k-split is highly sensitive to hub port configuration and transport mode selection. This indicates that in all the scenarios, mass flow influences decision because each transport mode's costs scales differently with volume and distance. Pipelines carry high fixed CAPEX but become cost-effective over short, high-flow routes, while ship-based modes (SHIP and DSI) scale with number of trips and remain competitive over longer distances. T Transport mode and storage allocation should therefore be optimised jointly. The main implication is that the competitiveness of DSI in the Mediterranean is network-specific. Its occurrence in a near-optimal configuration for a given connection depends not only on the distance and transport cost of that route, but also on the hub-port selection and on the amount of CO_2 allocated to the alternative storage sites. DSI occurrence rates should therefore be interpreted only within the context of an optimised network, and the same route may not remain competitive if assessed independently from the rest of the network.

5 Synthesis

The regional assessments show that the barriers to Direct Ship Injection are not uniform. Differences between regions reflect the physical and regulatory conditions, the maturity of each CCS chain and the assessment of the local teams.

The relevance of DSI depends on multiple issues, including the distribution and volume of the CO_2 sources, the distance between ports and storage sites, the maturity and injectivity of the storage resources, the availability of existing infrastructure, the regulatory framework, metocean conditions and the expected development of the transport network. Consequently, the barriers and opportunities

identified by the regional teams do not necessarily coincide and, in some cases, may lead to different conclusions. Such differences reflect the regional condition.

5.1 Cross-regional drivers and opportunities

The main driver for DSI across the four regions is its operational and network flexibility. DSI may connect several port hubs to an offshore storage site without requiring, from the start, a dedicated offshore pipeline or permanent injection platform. This is particularly relevant where captured volumes are initially limited or uncertain, emitters are geographically dispersed and the development of a large, shared transport network cannot yet be justified. Additional emitters, ports, vessels and storage sites may be incorporated progressively as the CCS chain develops.

A related opportunity is the possibility of reducing the time required to start offshore storage. DSI may allow transport and injection to begin while larger pipeline networks are still under development or before sufficient volumes have been secured to justify their construction. It may therefore support storage demonstration, early connection of industrial clusters and progressive development of regional CCS networks. This opportunity is particularly relevant in Portugal, the Baltic Sea and the Black Sea, where transport and storage systems remain at an early stage of development. In the North Sea, the opportunity results mainly from the availability of storage resources and offshore maturity of operations before the volumes required for new large-capacity pipelines are available.

DSI also provides opportunities for ports and maritime industries. Existing or planned ports may be used as CO_2 aggregation, conditioning and loading hubs, supporting activities in shipping, port operations, vessel services, subsea engineering and storage monitoring. These opportunities are particularly relevant in the North Sea, where the maritime and offshore industries are already established, but are also identified in Portugal, the Baltic countries and the Black Sea ports.

5.2 Cross-regional barriers and challenges

The main technical challenge is that the complete DSI operational cycle has not yet been demonstrated. Individual components are based on existing shipping, dynamic-positioning, pumping and subsea technologies, but their integration into a direct vessel-to-well injection system still requires pilot validation. The critical operations include connection of the subsea system, maintaining vessel position during injection, onboard CO_2 conditioning, control of the injection process, emergency disconnection and repeated reconnection under representative offshore conditions. The operational limits, availability and failure modes of the integrated system must be demonstrated before commercial deployment.

Batch injection is another important challenge. Injection occurs only while a vessel is connected to the well and will therefore require higher instantaneous injection rates than continuous pipeline injection. Injectivity, pressure response, thermal effects, well integrity, the required number of wells and reservoir behaviour during repeated injection and shut-in periods must be assessed for each reservoir. This is particularly important in the Baltic and Black Sea regions, where storage appraisal remains relatively immature, but it is also relevant in Portugal and the North Sea.

Metocean conditions directly affect the regularity of the transport and injection chain. Poor weather conditions may prevent vessels from sailing, connecting to the subsea system or dynamic positioning during injection. Port buffer storage may allow capture and liquefaction to continue during limited interruptions, but it cannot maintain offshore injection when the vessel is unable to operate. Experience from oil shuttle tankers provides a useful technical reference, particularly in the North Sea, but does not by itself demonstrate the operational regularity of DSI.

Regulatory uncertainty is the most recurrent non-technical barrier. Existing CCS, shipping and offshore regulations do not necessarily define the requirements applicable to direct vessel-to-well injection. Clear procedures are required for permitting the vessel–subsea interface, injection operations, monitoring, emergency disconnection, allocation of responsibilities and long-term liability. Cross-border chains also require coordination between the authorities responsible for the exporting country, maritime transport and the receiving storage site. This is a critical issue in the Baltic Sea, where national requirements must be considered together with the HELCOM framework, and in the Black Sea, where Romania and Ukraine have different regulatory status and levels of CCS maturity.

Commercial arrangements are also required before the flexibility of DSI can be converted into a reliable transport and storage service. These arrangements must address CO_2 quality specifications, responsibility for off-specification streams, capacity reservation, allocation of interruption risks, vessel and well scheduling, third-party access, tariffs, insurance and liability. They must also define which party finances, owns and operates the vessels, port infrastructure, buffer storage and subsea injection system. Uncertainty in the timing and volume of captured CO_2 affects the project risks and the economics of the CCS value chain. Risk mitigation and risk distribution are common issue across the whole CCS value chain. These issues should therefore also be considered for the DSI component of CCS projects. This could be achieved through derisking or risk sharing mechanisms at the EU or national level, while the technology matures to a full commercially viable scale.

DSI does not eliminate environmental and socio-economic impacts, but changes their nature compared with pipelines and conventional shipping. Avoiding a permanent platform or a long offshore pipeline may reduce construction-related disturbance and the linear seabed footprint. However, DSI introduces recurrent vessel presence over the storage site, dynamic-positioning noise, connection and disconnection operations, safety zones and specific accidental-release scenarios. These activities may interact with fisheries, commercial navigation, tourism, offshore wind, protected areas and other marine uses. Environmental assessment must therefore compare the actual impacts of the alternative configurations over their full operational lifetime. Stakeholder engagement should start during project definition, before exclusion zones, vessel routes and mitigation measures are fixed.

5.3 Regional specificities

The North Sea presents the most mature setting for DSI, with established offshore competence, developed storage regulation, multiple storage projects and an industrial base capable of supporting vessel and subsea operations. The geographical dispersion of Norwegian emitters and the expected transport of CO_2 from European sources provide a clear driver for maritime solutions. DSI may avoid the need for an offshore receiving platform and provide flexibility between different storage sites. The main remaining challenges are the demonstration of the complete connection and injection system, operational regularity under North Sea weather conditions, sufficient instantaneous injectivity, third-party access and coordination between transport and storage operators.

In Portugal, DSI may provide a transitional option for connecting the more distant Sines and Setúbal clusters to the storage site offshore Figueira da Foz. The main constraints are the maturity of the DSI technology, the absence of a defined permitting pathway, Atlantic metocean conditions and the need to coordinate DSI with the future national pipeline network. The relatively short offshore distance between Figueira da Foz and the storage site favours a pipeline connection for the central and northern sources, while DSI may retain value for the more distant southern clusters.

In the Baltic Sea, DSI provides flexibility for a cross-border system involving ports in Estonia, Latvia and Lithuania and a common offshore storage site in Latvia. Long transport distances from the Estonian and Riga ports, the possibility of progressively connecting additional emitters and avoidance of an

initial offshore platform are relevant opportunities. However, deployment depends first on clarification of the HELCOM and national regulatory frameworks, maturation of the E6 storage site, cross-border coordination and access to operators capable of developing and operating the offshore storage system.

Romania and Ukraine are assessed jointly because they share the Black Sea maritime setting, but their deployment conditions differ substantially. DSI may use existing or planned port infrastructure, reduce the need for extensive initial offshore infrastructure and support the progressive development of CCS clusters. The principal barriers are storage characterisation, regulatory and market maturity, uncertainty in future captured volumes and access to finance. In Ukraine, these limitations are compounded by the consequences of the war for industrial activity, port operations, maritime security, access to offshore assets, insurance and project implementation. The Black Sea assessment should therefore be interpreted as a regional replicability assessment rather than as evidence of equivalent readiness in Romania and Ukraine.

5.4 Mediterranean replicability

The Mediterranean assessment extends the analysis of suitability of DSI beyond the four CTS regions, albeit in an intentionally simplified manner. The assessment is exploratory and assesses only the offshore transport segment. It does not constitute a detailed feasibility assessment of DSI in Spain, France, Italy, Greece, Morocco or Egypt. Its main contribution to this deliverable is to show that DSI applicability is not limited to the four CTS regions and that it may become relevant in networks characterised by several national hubs, long maritime routes, shared storage sites and uncertain development sequences.

Under the assumptions adopted, DSI is not selected in the global minimum-cost configuration, but it appears in several near-optimal configurations, particularly for the France-Ravenna and Greece-Ravenna connections. These results identify routes where the avoidance of fixed offshore receiving infrastructure and the flexibility of direct injection may justify a more detailed assessment.

According to the assessment described in this report DSI should be regarded as a complementary and, in several regions, transitional component of offshore CCS networks. **Its strongest opportunities occur where volumes are initially uncertain, emitters are dispersed, storage is offshore and permanent infrastructure would delay the start of operations or impose excessive initial investment.** Its practical role must nevertheless be established for each value chain after the technical, regulatory, operational, environmental and commercial barriers identified in this deliverable have been addressed.

Table 6 - Cross-regional synthesis of the main DSI drivers, opportunities, barriers and potential deployment role

Region	Main drivers and opportunities	Main barriers and challenges	Potential role of DSI
Atlantic Coast of Portugal	Flexible connection of the distant Sines and Setúbal clusters to the storage site offshore Figueira da Foz; possibility of starting storage before completion of a national pipeline network; use of existing port infrastructure; connection of significant biogenic CO_2 sources.	DSI technology and the complete injection cycle remain to be demonstrated; no defined permitting pathway for direct ship-to-well injection; Atlantic metocean conditions may interrupt injection; batch operation requires adequate injectivity and buffer storage; DSI development must remain compatible with the future national pipeline network.	Mainly a transitional or complementary option for Sines and Setúbal. A pipeline connection is more likely to form the mature network for the central and northern sources, particularly given the short offshore distance between Figueira da Foz and the storage site.
Baltic Sea	Connection of emitters and ports in Estonia, Latvia and Lithuania to a common offshore storage site; long transport distances from the Estonian and Riga ports; progressive integration of additional emitters; possibility of avoiding the initial investment in an offshore receiving platform; potential integration of biogenic CO_2 sources.	Unresolved interaction between national requirements and the HELCOM framework; need for cross-border coordination; limited maturity of the E6 storage site; absence of detailed rules for DSI operations; limited regional offshore storage-operating capability; competition with navigation, fisheries, offshore wind and other marine uses.	A possible cross-border and phased deployment option, where flexibility and avoidance of a permanent platform justify its selection. Conventional shipping remains the lower-cost maritime configuration under the assumptions assessed in D3.1.
Black Sea - Romania and Ukraine	Existing or planned port infrastructure; offshore storage prospects in relatively shallow waters; possibility of developing CCS clusters without extensive initial offshore infrastructure; progressive connection of emitters as regional CCS markets develops.	Storage capacity and injectivity require further appraisal; regulatory and commercial frameworks remain immature; future captured volumes and project financing are uncertain. In Ukraine, the war imposes additional constraints related to industrial activity, port operation, maritime security, offshore asset accessibility, insurance and financing.	A potential transitional option for emerging CCS chains, but readiness must be assessed separately for Romania and Ukraine. The joint CTS assessment reflects the common Black Sea maritime setting and does not imply equivalent national deployment conditions.
North Sea	Mature offshore industry and storage regulation; dispersed Norwegian emitters and expected CO_2 imports from European sources; several prospective storage sites; possibility of avoiding an offshore receiving platform; existing	The complete vessel-to-well injection cycle has not yet been demonstrated; operational regularity under North Sea weather conditions remains uncertain; connector retrieval and emergency disconnection require validation; batch injection requires sufficient instantaneous injectivity; third-party access and	The most mature CTS setting for early DSI deployment, particularly for dispersed or initially limited volumes that do not justify new large-capacity pipelines. Its role depends on successful offshore

Region	Main drivers and opportunities	Main barriers and challenges	Potential role of DSI
	competence in shipping, dynamic positioning and subsea operations.	coordination between transport and storage operators remain to be defined.	demonstration and confirmation of full-chain operational performance.
Mediterranean replicability assessment	Network composed of several national port hubs, long maritime routes and shared storage sites; comparison of Spain, France, Italy, Greece, Morocco and Egypt with the Ebro, Ravenna and Prinos storage options; DSI appears in near-optimal configurations for the France–Ravenna and Greece–Ravenna connections.	The assessment covers only the offshore transport segment; results depend on assumed ports, CO_2 volumes, storage allocation, vessel and platform costs, injection capacity and financial parameters; regulatory, environmental, storage-development and operational barriers were not assessed in detail for each country.	An exploratory screening of DSI replicability beyond the four CTS regions. It identifies connections where detailed technical, regulatory, environmental and commercial assessment is justified, but does not demonstrate DSI feasibility in the Mediterranean.

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Annex A – Guiding questions and regional feedback

Guiding questions and answers relating to Atlantic Coast of Portugal region

Category and guiding questions (Provided as guidance - input those relevant for your region in 2nd column)	Region specific aspects (Atlantic coast of Portugal)	Relevance *	Recommendation
1. Regulatory Environment			
1. Are there regulations for transport of CO2 by ship?	1. No regulations for CO2 transport by ship	1. Important	1. It will follow the EU regulations developed for CO2 transport that will be applied directly to Portugal
2. Could permits be faster/easier compared to pipeline installation?	2. It will depend on the regulatory framework for direct injection and pipeline	2. Critical	
3. Could the absence of offshore pipeline regulation be an opportunity?	3. It will depend on the regulatory framework for direct injection and pipeline	3. Important	3. The absence of regulations can be an opportunity for direct injection
2. Environmental Aspects			
1. Could noise impact of ships holding dynamic position for long periods be an issue?	1. Noise from ships can be significant for EIA concerning mammals.	1. Important	1. Specific recommendations for ships may be needed. Monitoring is required for mammals
2. Are pipelines and platforms an environmental concern (habitats, fishing..)	2. They are since our site is included in areas with some level of environmental protection	2. Minor to Important	2. Condct an EIA as required by law
3. Is direct injection an environmental concern?	3. Possible higher risks of pollution from the Direct Injection vessel	3. Minor to Important	
3. Socio-Economic Impacts			
1. Is visual impact from platforms a concern in your region ?	1. Visual impacts (or its perception) is relevant for tourism. There no platforms offshore in the country	1. Important	1. Continuous engagement with stakeholders and touristic operators
2. Any possible conflicts with stakeholders (fisheries, navigation, tourism)?	2. There are concerns from the fishing industry, but the creation of a sanctuary can be relevant to provide fish to areas outside the protectio	2. Important	2. Discussion with regulatory authorities and fisherman communities
3. Direct injection favour/unfavour jobs in the region (pports /platforms?	3. Direct injection may favor jobs creation and foster the local economy	3. Minor	
4. Social acceptance likely favour reversible solutions over fixed structures?	4. Social acceptance may be easier for a pipeline but it may depend on the jobs created in both options	4. Important	4. Development of a communication strategy
4. Technical Feasibility			
1. Are maritime conditions challenging (waves, wind, currents)?	During winter times there are periods with storms but it should be manageable for large ships with a proper DP system	1. Important	1. Manageable with intermmediate storage and additional cost
2. Are long non-operational periods anticipated due to weather windows?	2. Long probably not	2. Minor	2. Implementation of contigency plans
3.	3. It will be continuous	3. Important	
4. Does injectivity favour continuous or campaign-style injection?	4. In principle it will be always better to have continuous injection	4. Important	
5. Infrastructure & Logistics			
1. Is the distribution of CO2 sources favourable for transport to a port?	1. The distribution of CO2 sources seems to be clearly favourable for a pipeline solution	1. Critical	
2. Are there many small scale CO2 emitters in the region?	2. There are several but they are not being considered as they have other options for decarbonization	2. Minor	
3. Is a platform technically justified or unjustified for the expected capacity?	3. A permanent platform will not be needed since the site is too close to shore	3. Minor	
7. Maturity & Time-to-Market			
1. Is rapid deployment needed (2030 targets, ETS pressure)?	1. In the Portugues case, to comply with the national commitments and the EU ETS, a rapid deployment is needed	1. Critical	1. Policy barriers must be addressed
2. Are pilot or early-stage projects expected?	2. Yes	2. Critical	2. To demosntrate the storage capacity and to validate the storage site
3. Does direct injection accelerate deployment relative to platform/pipeline?	3. Yes. It allows for flexibility in the early stages of development	3. Important	3. Engagement with the industry
8. Site-Specific Geological Factors			
1. Is reservoir injectivity suitable for intermittent injection?	1. In prnciple, no significant constraints from geological factors	1. Important	1. Appraisal injection well to confirm injectivity
2. Are only 1–2 wells available initially?	2. No wells available	2. Minor	
3. Is the site remote, deep-water, or expensive for platform installation?	3. The site is close to shore and in shallow waters (no platform is needed)	3. Minor	
9. Opportunities (Drivers)			
What are the strongest arguments **in favour** of direct injection in your region? Economic? Regulatory? Environmental? Time-to-market?	1. Direct injection can promote flexibility and can be a good option to consider during the pilot phase.	1. Critical	
	2. Some of the main emitters may be located far from the storage site, thus promoting ship transport during the initial phases.	2. Important	
	3. Direct injection can avoid complex permitting and multiple administrative approvals for some parts of the pipeline network (southern sources)	3. Minor to Important	
10. Barriers (Challenges)			
What are the main barriers that **could hinder** direct injection deployment?•Technical? Social? Policy? Market? Geological?	1. The continuous availability of CO2, the distribution of CO2 sources are likely the main barriers that could hinder direct injection	1. Critical	
	2. A pipeline solution can be a more robust one in the long-term, particularly in the cases where sources are close located to the storage site	2. Critical	

Category and guiding questions (Provided as guidance - input those relevant for your region in 2 nd column)	Region specific aspects (Baltic)	Relevance *	Recommendation
1. Regulatory Environment			
1. Are there regulations for transport of CO2 by ship?	1. No	1. Critical	1. Recommend to policy makers to prepare regulations
2. Could permits be faster/easier compared to pipeline installation?	2. Could be, yes	2. Critical	
3. Could the absence of offshore pipeline regulation be an opportunity?	3. Yes	3. Critical	
2. Environmental Aspects			
1. Could noise impact of ships holding dynamic position for long periods be an issue?	1. No data	1. Not relevant	
2. Are pipelines and platforms an environmental concern (habitats, fishing..)	2. Yes	2. Critical	
3. …			
3. Socio-Economic Impacts			
1. Is visual impact from platforms a concern in your region ?	1. No platforms available	1. Not relevant	
2. Any possible conflicts with stakeholders (fisheries, navigation, tourism)?	2. maybe	2. Minor to important	2. Needs study
3. Direct injection favour/unfavour jobs in the region (pports /platforms?	3. The relatively same number of jobs	3. Minor	
4. Social acceptance likely favour reversible solutions over fixed structures?	4. No data, additional data is required	4. Minor	4. Social study is needed
4. Technical Feasibility			
1. Are maritime conditions challenging (waves, wind, currents)?	1. Could be wind	1. Minor	
2. Are long non-operational periods anticipated due to weather windows?	2. Could be	2. Important	
3.	3. Continuous	3. Critical	
4. Does injectivity favour continuous or campaign-style injection?	4. Continuous		4. Agreements with CO2 producers are needed
5. Infrastructure & Logistics			
1. Is the distribution of CO2 sources favourable for transport to a port?	1. Yes	1. Important	
2. Are there many small scale CO2 emitters in the region?	2. Yes, but they are not included in scenario	2. Not relevant	
3. Is a platform technically justified or unjustified for the expected capacity?	3. Yes		
7. Maturity & Time-to-Market			
1. Is rapid deployment needed (2030 targets, ETS pressure)?	1. Yes	1. Critical	to local ministries is recomended to financially support feasibilities studies, as pilot injectivities.
2. Are pilot or early-stage projects expected?	2. Yes	2. Critical	
3. Does direct injection accelerate deployment relative to platform/pipeline?	3. Yes	3. Important	
8. Site-Specific Geological Factors			
1. Is reservoir injectivity suitable for intermittent injection?	1. Both options possible, no exact data	1.Important	
2. Are only 1–2 wells available initially?	2. Yes		
3. Is the site remote, deep-water, or expensive for platform installation?	3. No, no, no		
9. Opportunities (Drivers)			
What are the strongest arguments**in favour** of direct injection in your region? Economic? Regulatory? Environmental? Time-to-market?	1. Economic, 2. time-to-market	1. Important	We will have economic savings owing to long ship distances, but much closer and cheaper than to the North Sea
	Environmental assessment is not ready	2. Critical	
10. Barriers (Challenges)			
What are the main barriers that**could hinder** direct injection deployment?•Technical? Social? Policy? Market? Geological?	1. Policy regulations are not ready yet, 2. market is under development. 3. Onshore infrastruture is not ready	1. Critical	We need political decisions, national financial support, planning of onshore and port infrastructure, EC financial support
		3. Important	

Category and guiding questions (Provided as guidance - input those relevant for your region in 2 nd column)	Region specific aspects (Black Sea)	Relevance *	Recommendation
1. Regulatory Environment			
1. Are there regulations for transport of CO2 by ship?	in practice	1. Critical	1. Recommend regulators to develop regulations
2. Could permits be faster/easier compared to pipeline installation?	2. Yes - cross-border pipeline permits and security risks	2. Important	2. Ships can be implemented in earlier CCS projects
3. Could the absence of offshore pipeline regulation be an opportunity?	3. Yes	3. Important	
2. Environmental Aspects			
1. Could noise impact of ships holding dynamic position for long periods be an issue?	1. Yes, depending of the status of the area; depends on proximity to protected marine areas and fisheries	1. Minor	1. Check the interference with other activities in the area; conduct Marin EIA; assess seasonal fisheries impact
2. Are pipelines and platforms an environmental concern (habitats, fishing..)	2. It can be - seabed disturbance, fisheries interference, UXO risks (due to military context), protected coastal zones	2. Important	2. Check the interference with other activities in the area and check environmental protection status of the area
3. Could CO2 potential leaks from pipelines or Direct Injection compromise habitats?		1. Minor	3. Conceptual geochemical modeling
3. Socio-Economic Impacts			
1. Is visual impact from platforms a concern in your region ?	1. No; higher concern only if near coastal tourism areas (Odesa region, Ukraine)	1. Not relevant –Minor	
2. Any possible conflicts with stakeholders (fisheries, navigation, tourism)?	2. Yes, possible conflicts could appear with fisheries and commercial shipping lanes; security zones must be considered	2. Important	2. Consultation, information and awareness campaigns with stakeholders; coordinate with port authorities
3. Direct injection favour/unfavour jobs in the region (pports /platforms?	3. Positive for ports (handling, logistics, monitoring), limited offshore job creation	3. Important	3. Check the social benefits for Direct Ship Injection; provide touristic component; emphasize port-based value chain and monitoring services
4. Social acceptance likely favour reversible solutions over fixed structures?	4. Always	4. Important	4. Presented as the main driver for Direct Ship Injection - flexible, low-permanence infrastructure
4. Technical Feasibility			
1. Are maritime conditions challenging (waves, wind, currents)?	1. No usually, Black Sea can be impredictable - but winter storms possible; security risks must be considered	1. Minor	1. and 2. Check weather conditions over long period of time + security risk assessment
2. Are long non-operational periods anticipated due to weather windows?	2. No	2. Critical	
3.	3. Not sure	3. Critical	3. and 4. Establish with CO2 suppliers how they will deliver CO2; injectivity
4. Does injectivity favour continuous or campaign-style injection?	4. We do not know	4. Important	Conduct injectivity testing & dynamic modelling
5. Infrastructure & Logistics			
1. Is the distribution of CO2 sources favourable for transport to a port?	1. Yes - emitters concentrated in industrial regions with rail access to ports	1. Important	
2. Are there many small scale CO2 emitters in the region?	2. Yes for Ukraine, a few for Romania	2. Important	To integrate small emmitters into emmission clusters
3. Is a platform technically justified or unjustified for the expected capacity?	3. We do not know	3. Critical	NEMO preferable for pilot and early commercial phase
7. Maturity & Time-to-Market			
1. Is rapid deployment needed (2030 targets, ETS pressure)?	1. Yes for Romania (NZIA + ETS), EU CBAM pressure for Ukraine	1. Critical	Up to 2030 characterize reservoir and storage capacity
2. Are pilot or early-stage projects expected?	2. Yes for Romania, no for Ukraine	2. Important	Align Ukraine regulations with EU standards; press regulators to aid poli makers to find incentives and implement financial support programmes
3. Does direct injection accelerate deployment relative to platform/pipeline?	3. Yes – avoids waiting for pipeline network	3. Important	Promote NEMO as fast-track CCS solution
8. Site-Specific Geological Factors			
1. Is reservoir injectivity suitable for intermittent injection?	1. We do not know; data limited	1. Critical	Review available infrastructure and well integrity for CO2, legacy seismi & drilling data
2. Are only 1–2 wells available initially?	2. Yes for saline aquifers in Romania, not sure for Ukraine	2. Important	
3. Is the site remote, deep-water, or expensive for platform installation?	3. No, shallow water as storages (30-40m)	3. Important	Technically suitable for direct ship injection operations
9. Opportunities (Drivers)			
What are the strongest arguments**in favour** of direct injection in your region? Economic? Regulatory? Environmental? Time-to-market?	Time-to-market		Rapid deployment
	Unclear regulations for pipelines; fast permitting, low infrastructure needed (no platform less environmental impact compared to pipelines, good maritime conditions;		
	Reduced seabed disturbance; flexible & scalable solution; can serve as transitional model before full CCS network		
10. Barriers (Challenges)			
What are the main barriers that**could hinder** direct injection deployment?•Technical? Social? Policy? Market? Geological?	High costs compare with pipelines, public awareness; more research needed for storage sites and more modelling; unclear market; regulatory uncertainty (liability); limited geological data & injectivity confirmation; war-related maritime security risks		Start with regulatory sandbox / pilot framework + EU-supported pilot project

Guiding questions and answers relating to North Sea region

Category and guiding questions (Provided as guidance - input those relevant for your region in 2 nd column)	Region specific aspects (North Sea)	Relevance *	Recommendation
1. Regulatory Environment			
1. Are there regulations for transport of CO2 by ship?	In one of the pipelines to Hasold field be repursed, but might not be ready, OPE need to agree on use. Fiords / compl conditions for laying pipelines / distances	Important	We might need regulations for Direct Injection Ships. Denmark have it through greensand
2. Could permits be faster/easier compared to pipeline installation? YES	Lots of pipelines complicate permitting		
3. Could the absence of offshore pipeline regulation be an opportunity? NO	Lots of competitive economic activities		
2. Environmental Aspects			
1. Could noise impact of ships holding dynamic position for long periods be an issue?	1. Noise is not an issue	Minor	
2. Are pipelines and platforms an environmental concern (habitats, fishing..)	Sea infra-structures becomes "protection zone" for fish. More food, safe. Good for fish, bad for fishing industry		
3. …			
3. Socio-Economic Impacts			
1. Is visual impact from platforms a concern in your region ?	1. No. More impact of pipeline on the sea and fishing zones	Important	
2. Any possible conflicts with stakeholders (fisheries, navigation, tourism)?	2. Potentially with other industries no matter what as safety zones need to be established		
3. Direct injection favour/unfavour jobs in the region (pports /platforms?	3. No		
4. Social acceptance likely favour reversible solutions over fixed structures?	4. No		
4. Technical Feasibility			
1. Are maritime conditions challenging (waves, wind, currents)?	1. Yes, but we have decades of experience	Minor	
2. Are long non-operational periods anticipated due to weather windows?	2. Longer in the winter, needs modelling		
3.	3. To be seen, depends on proposal		
4. Does injectivity favour continuous or campaign-style injection?	4. In bottom be too to connect. Minor know to cont. case dependent		
5. Infrastructure & Logistics			
1. Is the distribution of CO2 sources favourable for transport to a port?	1. Yes. Long distances	Minor	
2. Are there many small scale CO2 emitters in the region?	2. Yes		
3. Is a platform technically justified or unjustified for the expected capacity?	3. New platforms too expensive. Subsea solution most likely, old platform could be an option. Unmanned with dry wells? Planning pipelines is very demanding		
7. Maturity & Time-to-Market			
1. Is rapid deployment needed (2030 targets, ETS pressure)?	1. Yes	Important	
2. Are pilot or early-stage projects expected?	2. Yes, also testing Greesand, Bifrost		
3. Does direct injection accelerate deployment relative to platform/pipeline?	3. Yes, Denmark has 3 Mtpa by 2050 comm		
8. Site-Specific Geological Factors			
1. Is reservoir injectivity suitable for intermittent injection?	1. Case dependent	Minor	
2. Are only 1–2 wells available initially?	2. Yes, case dependent		
3. Is the site remote, deep-water, or expensive for platform installation?	3. Danish is shallower and closer. Completely different approaches - Denmark chose close to infrastructure; Norway far away to avoid overlaps		
9. Opportunities (Drivers)			
What are the strongest arguments **in favour** of direct injection in your region? Economic? Regulatory? Environmental? Time-to-market?	Economic, flexibility, time to market	Critical	
	Ships seem to be more and more on agenda		
	Platform - big investment , volumes, long commitements		
10. Barriers (Challenges)			
What are the main barriers that **could hinder** direct injection deployment?•Technical? Social? Policy? Market? Geological?	"Untested", technical may be, market power - Ships/Direct Injection is more competitive	Critical	Open market / access
	Currently license owner controls the whole chain		How to involve small emitters

Annex B- Mediterranean network optimisation methodology

Italian and Spanish port selection needs furthermore screening to narrow down to the most optimum port. Therefore, all the scenarios are repeated for transport modes for possible different combinations of Spanish-Italian ports. Each combination represents a case. Therefore, **Cases** are defined for optimization of Spanish-Italian ports, within each Case, all the possible scenarios of transport modes are simulated to find out the best transport mode for all the connections.

Additionally, optimization of CO_2 mass split for France, Italy and Greece are done since these countries have more than one storage options. This optimization is performed in each scenario for these three countries. Mass split optimization is executed using MATLAB's *fmincon* solver with the *SQP* algorithm.

The complete simulation framework of the network optimisation methodology, as represented in Figure B.1, is divided into iterative scenarios and cases:

i. In each scenario, all three parts of the model are simulated for a particular combination of transport mode;
ii. In each scenario, discounted lifetime cost is calculated keeping a fixed transport mode for each isolated hub-reservoir connection by optimizing mass split between reservoirs;
iii. Discounted lifetime cost of each scenario is recorded using a cost feedback signal which is utilized to compare and find the best-case scenario with minimum objective function.
iv. These scenarios are repeated until all the possible combinations of transport modes selection for each hub-reservoir are simulated;
v. In each case, to find out the best Spanish and Italian ports, simulation iterations from step (i) to (iv) are repeated with all possible Spanish-Italian port combination variations.

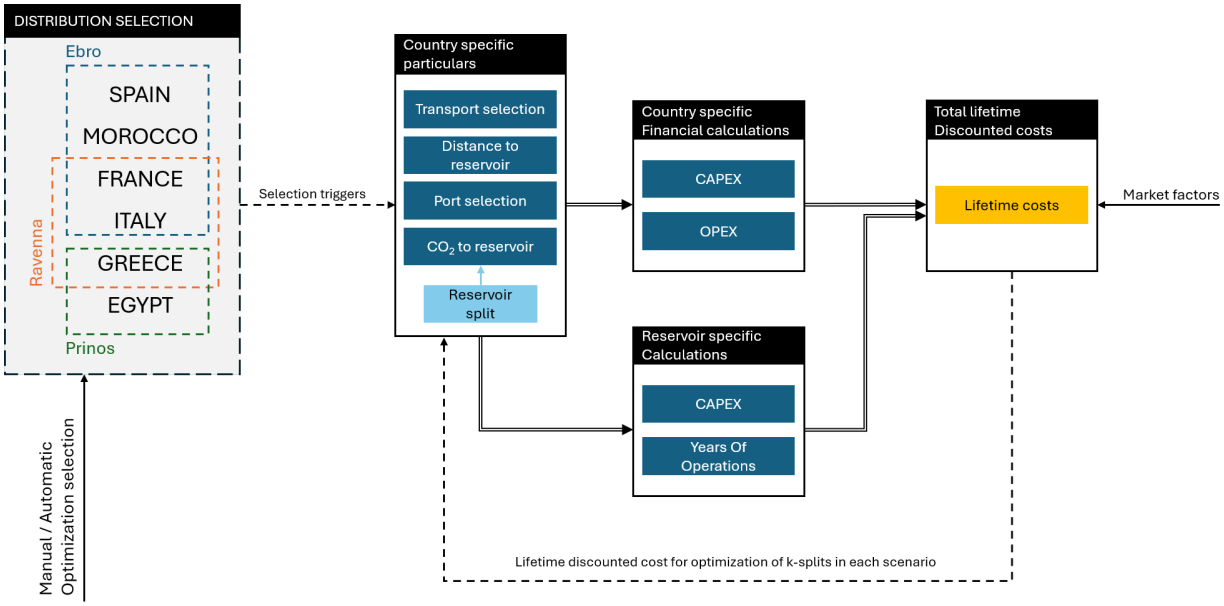


Figure B.1. Overview of MATLAB/Simulink model workflow for transport selection, cost calculation, and lifetime discounted cost optimization.

This framework is overall divided into three parts, which are described as follows:

Distribution and country particulars: This part of the model framework establishes key parameters for each connection along with calculation of dependent parameters that are required to estimate related CAPEX and OPEX. Key parameters like individual port selection, hub-reservoir distance, national CO_2 mass for CCS, reservoir storage capacity and transport mode for each scenario. Except transport mode, these are pre-determined factors for which all scenarios operate for every selected case. Dependent parameters are the added variables that are the function of key parameters and are required for financial calculations. These parameters are hub-reservoir CO_2 mass flow for every connection (also dependent of optimized k-splits), ship details, pipeline details and reservoir details. These parameters as summarized in Table B.1 are calculated as per the framework defined in D3.1.

Table B.1. Key and Dependent Distribution Parameters required for financial calculations.

	Parameters	**Sub parameters**
Key Distribution Parameters	Port selection	Spanish and Italian ports combination in each case
	Hub-reservoir distance	-
	National CO_2 for CCS	-
	Reservoir CO_2 storage capacity	-
	Transport mode	-
Dependent Distribution Parameters	CO_2 mass flow per connection	k-splits
	Ship details per connection	Loading time, injection time, round trip time, number of ships required, buffer storage at port and/or at offshore platform and CO_2 conditioning requirements.
	Pipeline details per connection	Pipeline length, pipeline cross-section and CO_2 conditioning requirements.
	Reservoir details	Number of required offshore platforms at each reservoir in case of CS and Number of injection hoses required in case of DSI.

Financial Calculations: Two parallel calculations pertaining to country and reservoir specific are carried out within this part. Sizing of equipment and infrastructure done using key and dependent distribution parameters are used to calculate their capital investment costs and estimated operational costs.

CAPEX of ship acquisition, pipeline laying and other related infrastructure (as described in D3.1) along with OPEX related to crewing, fuel, harbour fee for ship and maintenance in both the scenarios. Relating CAPEX and OPEX for each country and reservoir is calculated as per the framework set in D3.1 with the financial parameters mentioned in Table B.2.

For CO_2 injection, offshore platform is required with operational buffers on the platform in case of Conventional ships, whereas a flexible injection hose arrangement is required in case of Direct Injection Ships. In both the cases, it is assumed that each unit will be share by a maximum of 2 ships at the injection site which can be from the same country or different countries. For every couple of ships, a new offshore platform and/or injection hose needs to be deployed at the injection site. On the other hand, in case of pipeline, an umbilical cord needs to be installed for monitoring and controlling purposes with the same length as the pipeline.

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Table B.2. Financial parameters affecting CAPEX and OPEX of all the three modes of transportation (All the values referenced and consistent with Mesquita et al. (2026)).

Parameter	**Cost**	**Unit**
Conventional Ship (SHIP) CAPEX	289	M€/ship
Direct Injection Ship (DSI) CAPEX	329	M€/ship
Umbilical cord cost (u)	2	M€/km
CS Fixed OPEX	$0.02 \cdot CAPEX_{CS} \cdot (Number\ of\ CS\ ships)$	M€/yr
DSI Fixed OPEX	$0.02 \cdot CAPEX_{DIS}(Number\ of\ DIS\ ships)$	M€/yr
Pipeline Fixed OPEX	$0.03 \cdot (Terrain\ factor)$ $\cdot CAPEX_{Pipe}(Pipe\ weight\ per\ km)$	M€/km/yr
Umbilical cord Fixed OPEX	$0.03 \cdot u$	M€/km/yr

Objective function – Lifetime Discounted Costs: Lifetime Discounted Costs or Present Value (PV) is calculated using outputs of both the previous parts for each scenario. Being an objective function for the optimization algorithm as well, k-split values depend on this output. The optimization algorithm finds the most optimal combination of all three k-splits to minimize the Lifetime Discounted Cost for each scenario. The calculations use an inflation rate of 2.5% and a nominal discount rate of 5%, consistent with D3.1. The cost is the function of CAPEX and OPEX for all the six countries (denoted by c) along with CAPEX of all the reservoirs obtained from previous part and can be expressed as following formula for each scenario i:

$$PV_i = \sum_{c=1}^{6} CAPEX_c + CAPEX_{reservoir\ total} + \sum_{c=1}^{6} OPEX_{c_{PV}}$$

Operational year of each connection is equal to the operational years of the reservoir (t_r) storage capacity of the reservoir and CO_2 injected each year from all the possible countries (with the maximum limit of 30 years). The latter is decided by the k-split factor and therefore, this k-split factor not only affects infrastructure sizing, but also operational years of all the selected connections. $OPEX_{c_{PV}}$ for every connection (c, r) is calculated using the following equation:

$$OPEX_{c_{PV}} = \sum_{r=1}^{3} OPEX_{c,r}\ \varphi \frac{\varphi^{t_r} - 1}{\varphi - 1}, \qquad \varphi = \left(\frac{1 + IR}{1 + DR}\right)\ \&\ DR \neq IR$$

Annex C – Quantitative approach to forecasting future industrial emissions

Future decarbonization measures are considered per sector (again except Egypt). Since each industry is expected to follow an independent roadmap for decarbonization, an emission factor of decarbonization is estimated for each industry. This factor is assumed to be common for each country. This factor is multiplied by reported fossil emissions of 2023. A sector-specific decarbonization factor is used, as shown in Table C.1, to forecast emissions available for capture.

For Chemicals, Iron & Steel, Refineries, Power, Cement, Lime, Energy from waste and Hydrogen industrial sectors, this decarbonization factor is sourced from Shogenova, A. et al. (2024). In case of pulp and paper, it is a conservative assumption based on calculations done in the sector whereas, in case of Aluminium production, the 0.25 factor is based on the findings of Zore, L. (2024)[42] (15% direct emissions and 10-11% thermal requirements). Remaining 0.5 and 0.35 decarbonization factors corresponding to non-iron metals and ammonia are estimated assumptions made based on literature available.

Only those sources with remaining emissions above a threshold of 0.1 Mt/yr are considered in the analysis. This narrows down the number of emitters to a more realistic value and filters out those for whom CCS makes economic sense. In Morocco, narrowed down emitters are spatially distributed and, therefore, directed to the closest port hub, Nador.

Table C.1 Industry specific emission factor accounting for future decarbonization measures

Industry	**Decarbonization factor**
Chemicals (other)	0.35
Iron & Steel	0.25
Refineries	0.5
Power	0.5
Cement	0.65
Lime	0.65
Energy from waste	0.8
Hydrogen	0.3
Paper and pulp	0.5
Non iron metals	0.5
Aluminium	0.25
Ammonia	0.35

[42] Decarbonisation options for the aluminium industry - Publications Office of the EU

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