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

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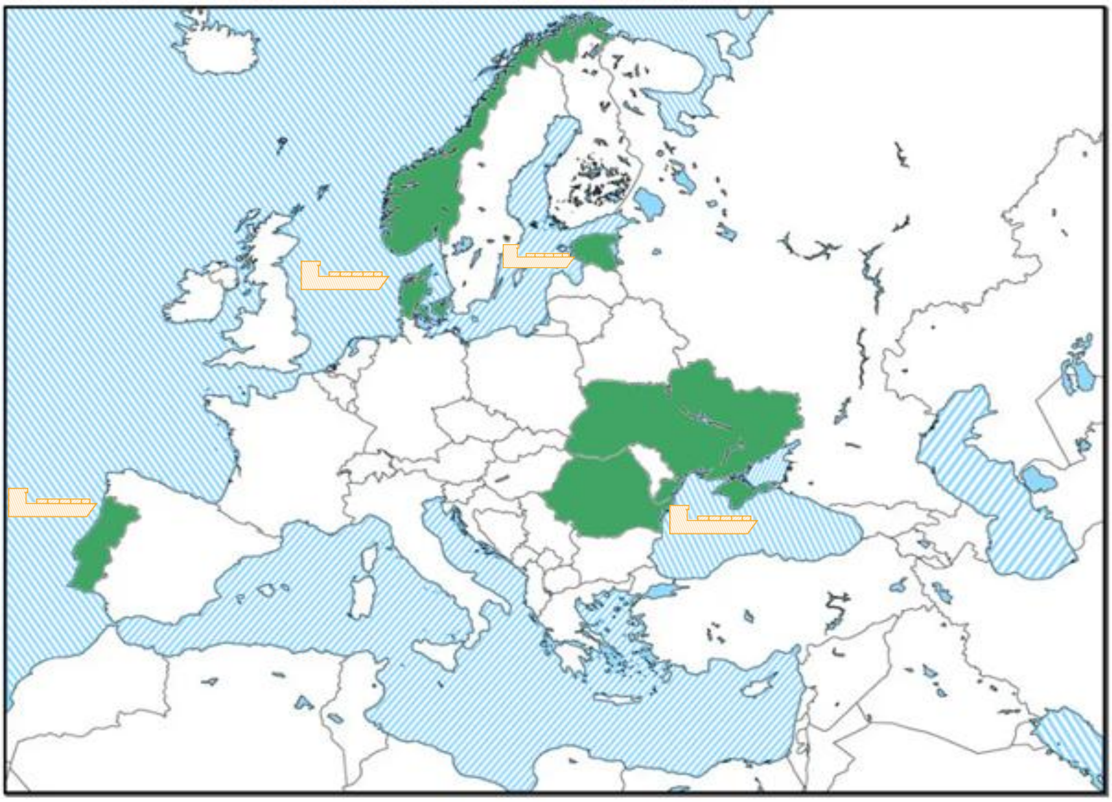

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Executive Summary

This report includes a regulatory background and an outline of CTS CCS/CCUS scenarios in four offshore regions in different parts of Europe. About 85 Mt/y CO_2 are planned to be transported to and from 22 ports with a shipping distance of more than 9000 km. This report summarises work in WP2, preparing the data for further techno-economic modelling in the WP3 of the CTS project.

The regulatory background includes International and Regional CCS Regulations, showing the readiness and challenges of different offshore storage regions and countries to demonstrate and implement CCS. The regulatory chapter contains recommendations to help national and regional authorities, organisations and stakeholders take needed regulatory actions as soon as possible to reach planned national energy and climate targets by 2030, 2040 and 2050 deadlines.

The most complicated scenario with the most significant impact on climate change is proposed for the North Sea. It includes, in total, seven CO_2 emission clusters in Denmark and Norway, with 30 emitters capturing about 14 Mt/y CO_2 and about 40–60 Mt/y CO_2 transported from four North Sea European ports in Germany, France, Belgium and The Netherlands. About 54–76 Mt/y CO_2 will be transported and stored under the North Sea in the storage formations, including DOF (depleted oil fields) and DSA (deep saline aquifers) in Denmark and DSA in Norway.

The Baltic Sea scenario includes three Baltic States (Estonia, Latvia and Lithuania) with four clusters, 16 emitters and one storage site in DSA offshore Latvia. More than 8 Mt CO_2 will be transported from four Baltic Sea ports and stored annually in an E6 structure in Latvia, while 0.9 Mt CO_2 can be used. Estonia's CO_2 mineral carbonation project is included in the Baltic Scenario as an example of a CO_2 case with possible future application of bio-CO_2 and CO_2 use increase in all three Baltic States. CO_2 use case for CO_2 mineral carbonation with oil shale ash (BOS) for production of PCC will utilise about 0.25 Mt/y CO_2 and 1.3 Mt/y of OSA to produce 0.5 Mt/y PCC. This case will not be considered for the economic modelling of the Baltic CTS scenario in WP3.

The Black Sea Scenario consists of Romanian and Ukraine scenarios, including capturing 2.1 Mt/y CO_2 in Romania and 1.2 Mt/y CO_2 in Ukraine. In Romania, captured CO_2 will be transported to one DSA and one DOF from one port located 75 km from DSA, while in Ukraine, three DGF will be used for storage of CO_2 transported from two ports in the Black Sea with a total distance from ports is more than 960 km.

The Western Coast of Portugal scenario will transport 8.3 Mt CO_2 from 24 plants (6 clusters) to four ports and from ports to one storage site (DSA). The total distance from ports is 875 km.

The North Sea and Western Coast of Portugal scenarios have readily needed regional and national regulations for offshore storage. In contrast, Baltic and Black Sea scenarios are more challenging, with regulations not permitting in Latvia, the Baltic and Black seas, and regulations unavailable in Ukraine.

Baltic and Black Sea regions need changes in national and regional regulations, including a rising ban on CO_2 storage in Latvia, implementation of CCS regulations in Ukraine and CCS regulations by Helsinki and Black Sea Conventions.

Table of Contents

Abbreviations and Units 6

Abbreviations 6

Units 7

1. Introduction 8

2. Methodology 8

3. International and Regional Regulations 10

3.1 Multilateral Environmental Agreements 10

3.1.1 London Convention 10

3.1.2 London Protocol 10

3.1.2.1 Amendment to Article 6 11

3.1.2.2 Provisional Application of the 2009 Amendment to Article 6 of the LP 12

3.1.3 OSPAR Convention 13

3.2 Regional Regulations 14

3.2.1 Helsinki Convention 14

3.2.2 Black Sea Convention 16

3.3 Summary of National, Regional and International Regulations for the CTS Regions 17

3.4 Regulatory recommendations for the CTS regions 18

4. North Sea Scenario 20

4.1 Introduction 20

4.2 CO_2 emissions 21

4.3 CO_2 Storage Sites 24

4.4 CO_2 Transport 27

4.4.1 Ports 27

4.4.2 Shipping Routes 28

4.4.3 Pipeline Routes 31

4.7 CO_2 Use 32

4.8 Summary 32

5. Baltic Sea Scenario 35

5.1 Introduction 35

5.2 CO_2 emissions: Decarbonisation and CO_2 Management in the Baltic States 36

5.2.1 Estonia 37

5.2.2 Latvia 39

5.2.3 Lithuania 39

5.3 CO_2 Storage Site ... 40
5.4 CO_2 Transport ... 44
5.5 CO_2 Use ... 46
5.5.1 CO_2 Use Case in Estonia ... 47
5.6 Summary ... 48
6. Black Sea Scenario ... 50
6.1 Romania ... 50
6.1.1 Introduction ... 50
6.1.2 CO_2 Emissions ... 51
6.1.3 CO_2 Storage Sites ... 53
6.1.4 CO_2 Transport ... 59
6.1.5 Summary ... 64
6.2 Ukraine ... 65
6.2.1 Introduction ... 65
6.2.2 CO_2 Emissions ... 65
6.2.2.1 Odesa Region ... 66
6.2.2.2 Mykolaiv Region ... 67
6.2.3 CO_2 Storage Sites ... 67
6.2.3.1 Storage Sites Description ... 67
6.2.3.2 CO_2 Storage Capacity ... 69
6.2.4 CO_2 Transport ... 70
6.2.4.1 Ports ... 70
6.2.4.2 Pipelines ... 71
6.2.4.3 Ship Routes ... 72
6.2.5 Summary ... 74
7. Western Coast of Portugal ... 76
7.1 Introduction ... 76
7.2 CO_2 Emissions ... 77
7.3 CO_2 Storage Site ... 81
7.4 CO_2 Transport ... 84
7.5 CO_2 Use ... 87
7.6 Summary ... 87
8. Comparison of Scenarios ... 89
9. Conclusions ... 92

Abbreviations and Units

Abbreviations

BOS – Burnt Oil Shale

CCS – CO_2 Capture and Storage

CCU – Carbon Capture and Utilisation

CCUS – CO_2 Capture, Utilization and Storage

CO_2 – Carbon Dioxide

CP – Cement Plant

DEA – Danish Energy Agency

DGF – Depleted Gas Field

DOF – Depleted Oil Field

DSA – Deep Saline Aquifer

EU – European Union

EU ETS – European Union Emission Trading System

EPRT – European Pollutant Release and Transfer Register

GHG – Greenhouse Gas

GIS – Geographic Information System

GWP – Global Warming Potential

ISO – International Standard Organisation

LCO_2 – liquid CO_2

MRV – Monitoring, Reporting and Verification

N - Number

NCT – National Carbon Tax

NECP – National Energy and Climate Plans

OSA – OIL Shale Ash

PCC – Precipitated Calcium Carbonate

PCI – Project of Common Interest

PP – Power Plant

QGIS – is an open-source geographic information system

SPA – Special Protection Area

T&S – Transport and Storage

TEA – Techno-Economic Analysis

WtE – Waste-to-Energy

Units

% – Percentage

°C – Degrees Celsius

g/l – gram per litre

kg – kilogram

kg/m^3 – kilograms per cubic metre

kg/s – kilograms per second

km – kilometre

km^2 – square kilometre

kt – kiloton

kt/y – kiloton per year

kW – kilowatt

kW/h – kilowatt per hour

l – litre

m – metre

m/s – metres per second

mD – milli Darci

MPa – mega Pascal

Mt – million tonnes

Mt/y – million tonnes per year

MW – megawatt

MWh – megawatt hours

t – tonne

T, ˚C – temperature by Celsius

t/hr – tonne per hour

t/y – tonnes per year

TJ – Terajoule

W – watt

W/m^2K – watts per square meter per kelvin, SI unit for heat transfer coefficient

1. Introduction

The report includes compiling the CCS/CCUS offshore scenarios in four offshore regions for implementation and further techno-economic modelling of CTS technology.

The North Sea scenario includes CO_2 emissions and CO_2 storage sites in Norway and Denmark, as well as the import of CO_2 emissions from four EU countries transported from North Sea European ports for storage in the North Sea region.

The Baltic Sea scenario includes CO_2 emissions from three Baltic countries (Estonia, Latvia and Lithuania), transported by pipelines to four Baltic Sea ports and from ports to CO_2 storage site (DSA) offshore Latvia by ships, and CO_2 use mineral carbonation case in Estonia.

Black Sea scenario includes a) Romanian scenario with CO_2 emissions from two clusters transported to one port by different transport options (rail, road, short pipelines and fluvial) and from the port to offshore storage sites (DSA and DOF) in the Romanian national waters, while b) Ukrainian scenario includes CO_2 emissions from two Ukrainian regions (Odesa and Mykolaiv), transported to two ports and from ports to three storage sites (DGFs) in the Black Sea using offshore pipelines, or ships and pipelines.

The Western Coast of Portugal scenario is a national scenario in Portugal, including CO_2 emissions from several CO_2 emission clusters transported by pipelines to four ports and from ports to one offshore CO_2 storage site (DSA).

The data collected and technical arrangements from this report will be applied in WP3 techno-economic modelling of CTS technology, where final technical parameters could be either like in this report or modified to improve the techno-economic parameters of the proposed scenario.

The report starts with an overview of the methodology used. It then proceeds with a non-technical chapter on International and Regional CCS Regulations, underlying the importance of the regulatory basis, readiness and challenges of different offshore regions and countries to demonstrate and implement CCS technology. This chapter is finished with regulatory recommendations that aim to help national and regional authorities, organisations, and stakeholders take needed regulatory actions as soon as possible, permitted to reach planned national energy and climate targets by 2030, 2040 and 2050 deadlines. Finally, all four regional scenarios are presented.

2. Methodology

The reported scenarios in four offshore regions have different arrangements summarised in Chapter 8 but unified methods and approaches. CO_2 fossil emissions, mainly produced by power and industrial plants in 2023 or, in some cases, in 2022, were collected from EU ETS[1] for EU countries and Norway (not available for Ukraine). Bio-CO_2 emissions were, however, gathered differently. For Portugal, some emitters provided bio-CO_2 emissions. In some cases, they were calculated using total CO_2 emissions from the EPRT[2] database and fossil CO_2 emissions from EU ETS. Danish emitters were

[1] EC. (2024). *EU Emissions Trading System (ETS) compliance management*. https://ec.europa.eu/clima/ets/allocationComplianceMgt.do

[2] European Industrial Emission Portal. https://industry.eea.europa.eu/industrial-site/environmental-information?siteInspireId=DK.CAED%2F000048306.SITE&siteName=Fortum%20Waste%20Solutions%20A%2FS&siteReportingYear=2022

assumed to use several produced materials. In other cases (like Estonia), bio-CO_2 emissions were collected in the national environmental emissions register[3].

Individual CO_2 emissions were not collected for North European clusters of plants in the North Sea scenario, while North European ports were included with publicly announced plans for becoming CO_2 hubs.

A similar approach was applied to CO_2 emissions in the Ukrainian part of the Black Sea Scenario. Due to the ongoing war, only regional CO_2 emission data was available for two Ukrainian regions, taken from Environmental Reports[4] of 2023 at the State Statistics Service of Ukraine.

Most scenarios applied 95% of capture efficiency to calculate the captured CO_2 emissions. Additionally, the Baltic scenario applied 10% for the CO_2 use case, which is described in more detail for the Estonian CO_2 mineral carbonation project and in more general assumptions for all Baltic States.

Mainly, static CO_2 storage capacities were calculated for DSA, DGF, and DOF using formulas and approaches proposed in the EU GeoCapacity project[5] and principles applied by the US DOE to calculate storage efficiency[6][7] in most of the included scenarios.

The exact formulas and approaches were used to calculate static storage capacity for storage sites in Denmark, which are available in public reports and other public sources.

In the North Sea Scenario, storage capacity for the Norwegian Continental Shelf is available for fields or formations, as estimated by the Offshore Directorate[8].

The storage capacity of the E6 structure offshore Latvia in the Baltic Scenario was estimated in the previous publications[9]. This report estimated the storage capacity of DOF and DGF in the Black Sea scenario. The storage capacity of the storage site in Portugal is based on the results of the CCS Strategy project.

For the Western Coast of Portugal scenario, the selected reservoir for CO_2 storage was deeply studied in the PilotSTRATEGY project; the reservoir properties considered were based on reports and publications of that project, which is still ongoing.

For selecting CO_2 emitters, we mainly applied the following approaches:

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3 Estonian Environmental Registry. (2024). *Annual reports registry*. Estonian Ministry of the Environment. https://kotkas.envir.ee/annual_reports_registry?represented_id=

4 https://mepr.gov.ua/diyalnist/napryamky/ekologichnyj-monitoryng/ekologichni-pasporty/

5 Vangkilde-Pedersen, T., Anthonsen, K., Smith, N., Kirk, K., N, F., Van der Meer, B., Le Gallo, Y., Bossie-Codreanu, D., Wojcicki, A., Le Nindre, Y., Hendricks, C., Dalhoff, F., Christensen, N. (2009). Assessing European capacity for geological storage of carbon dioxide – the EU GeoCapacity project, Energy Procedia 1 (2009) 2663-2670.

6 US Department of Energy (US DOE). (2008). Methodology for development of geological storage estimates for carbon dioxide. 1-37.

7 Goodman, A., Hakala, A., Bromhal, G., Deel, D., Rodosta, T., Frailey, S., Samll, M., Allen, D., Romanov, V., Fazio, J., Huerta, N., McIntyre, D., Kutchko, B. and Guthrie, G. (2011). U.S. DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale. International Journal of Greenhouse Gas Control, 5 (4), 952–965. https://doi.org/10.1016/j.ijggc.2011.03.010.

8 CO_2 atlas for the Norwegian Continental Shelf. CO2 atlas for the Norwegian Continental Shelf - The Norwegian Offshore Directorate

9 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.

1) Primarily significant emissions (> 100 Kt CO_2) were selected (except in some cases in Norway and Portugal).
2) They are located close to the ports (except for some cases where more distant stakeholders with established connections were included).
3) The ports most suitable for constructing large CO_2 terminals or those already included in EU PCI and CCUS projects were selected.
4) The most suitable transport options included pipelines, railways, trucks, and river vessels to transport CO_2 to ports.

3. International and Regional Regulations

3.1 Multilateral Environmental Agreements

At the international level, the most essential regulations affecting CCS are the international conventions dealing with the transboundary shipments of CO_2. These include the Protocol to the *Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter* (London Protocol) and the Convention for the Protection of the Marine Environment of the North-East Atlantic (known as the *OSPAR Convention)*. Among CETP CTC countries, Portugal, Norway, and Denmark are members of OSPAR and the EU. At the same time, Denmark, Estonia, Latvia, and Lithuania are members of the HELSINKI Convention, along with the EU, and Romania and Ukraine are members of the Black Sea Convention.

3.1.1 London Convention

The London Convention, adopted in 1972, is an international agreement on waste disposal at sea. It was one of the first global conventions on protecting the marine environment and has been administered by the International Maritime Organisation since 1977. The Convention prohibits dumping hazardous materials and requires a special permit for others. It defines 'dumping' as the deliberate disposal of waste from ships, aircraft, platforms, or other artificial structures. Amendments in 1993 banned the dumping of low-level radioactive waste at sea and phased out the dumping of industrial waste by December 1995. There are 87 States Parties to the 1972 London Convention[10] (Figure 1).

3.1.2 London Protocol

In 1996, Parties of the London Convention adopted a "*Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter of 1972*", known as the London Protocol (LP). The LP entered into force in 2006. The LP is a separate treaty from the Convention and may be ratified by States not part of the Convention.

The LP is the more modern and comprehensive of the two global treaties that prevent marine pollution by dumping at sea. It provides the precautionary framework needed for parties to effectively prevent sea pollution caused by dumping waste and other matter, incineration, and new activities such as marine geoengineering or carbon capture and storage. Nowadays, the LP is one of the key pillars of marine environmental protection within the international regulatory framework, along with the MARPOL, UNCLOS, and Regional Seas Agreements.

In December 2023, the London Protocol 1996 counted 54 Parties, and 87 parties were members of the London Convention 1972[10] (Figure 1). The Protocol, which is meant to replace the 1972 Convention

[10] International Maritime Organization (IMO). (2023). *Map of current LC/LP parties (December 2023)* [PDF]. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/LC_LP/Map%20of%20Parties%20(December%202023).pdf

eventually, represents a significant change of approach to the question of how to regulate the use of the sea as a depository for waste materials. Rather than stating which materials may not be dumped, it prohibits all dumping, except for possibly acceptable wastes on the so-called "reverse list" included in an annexe to the Protocol.

The London Protocol stresses the "*precautionary approach*", which requires that "*appropriate preventative measures are taken when there is reason to believe that wastes or other matter introduced into the marine environment are likely to cause harm even when there is no conclusive evidence to prove a causal relation between inputs and their effects*"[11]. It also emphasises that the principle that "*the polluter should, in principle, bear the cost of pollution" should not be seen as a mere transfer of pollution costs* ". The effects of rising CO_2 levels on the marine environment and the control of new climate engineering technologies are also addressed by the London Convention and Protocol. These advanced international regulatory instruments focus on CCUS in subsea geological formations and marine climate engineering, such as ocean fertilisation.

The 1996 Protocol restricts all dumping actions except those considered permitted and listed in Annex 1 (which still requires permits). In 2007, the amendment entered into force, and the Protocol Parties adopted "*Specific guidelines for Assessment of Carbon Dioxide Streams for Disposal into Sub-seabed Geological Formations*".

Article 4 of the LP states that LP Parties "*shall prohibit the dumping of any wastes or other matter except those listed in Annex 1*". The CO_2 streams from CO_2 capture processes are in the list of permitted substances. The amendments state that CO_2 disposal is permitted only into a sub-seabed geological formation, carbon dioxide streams should consist overwhelmingly of carbon dioxide (they may contain incidental associated substances derived from the source material and the capture and sequestration processes used), and no wastes or other matter are added to dispose of the CO_2 streams.

3.1.2.1 Amendment to Article 6

An amendment was adopted in 2009 to address the potential incompatibility between Article 6 of the LP and CCS activities. The former Article 6 prohibits the "export of wastes or other matter to other countries for dumping or incineration at sea", while the 2009 amendments Article 6 (LP.3(4)) enable - exclusively - the export of carbon dioxide streams for sequestration in transboundary sub-seabed geological formations.

However, this amendment has not yet been enacted as only 12 countries have adopted it by November 2024. By November 2024, it was accepted only by 12 countries: Norway and the UK in 2011, The Netherlands in 2014, Iran in 2016, Finland in 2017, Estonia in 2019, Sweden in 2020, Denmark, Belgium and the Republic of Korea in 2022, Switzerland in January 2024 and Australia in October 2024. Nine of these 12 countries sent IMO declarations with a provisional application of the 2009 amendment to Article 6 of the London Protocol (all the listed countries except for Estonia, Finland, and Iran)[12]. However, the amendment to the LP requires acceptance by two-thirds of the Parties to enter into force.

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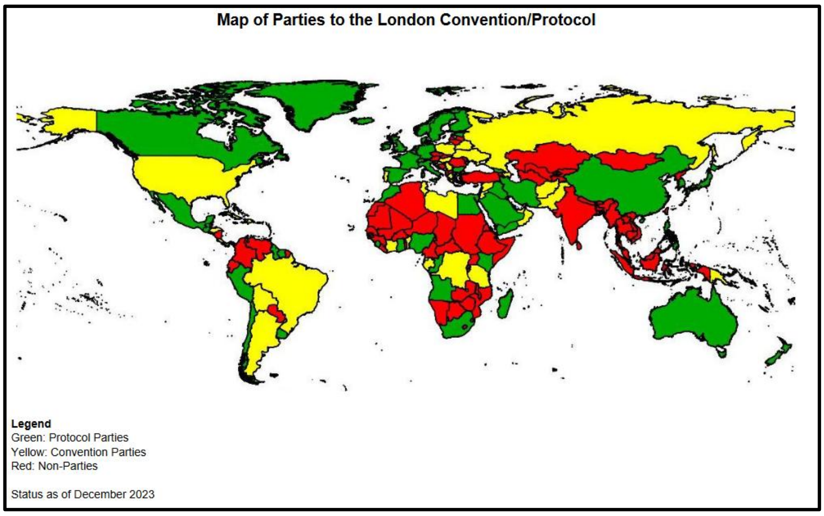
[11] London Protocol. (2006). *Article 3*. https://www.epa.gov/sites/default/files/2015-10/documents/lpamended2006.pdf

[12] International Maritime Organization (IMO). (2024). *Status of IMO treaties: Comprehensive information on the status of multilateral conventions and instruments* (pp. 585-592). https://wwwcdn.imo.org/localresources/en/About/Conventions/StatusOfConventions/Status%202024.pdf

3.1.2.2 Provisional Application of the 2009 Amendment to Article 6 of the LP

The fourteenth Meeting of the Contracting Parties to the Protocol was decided on October 11, 2019, to allow for the provisional application of the 2009 amendment pending its entry into force by those Contracting Parties that have deposited a declaration to this effect.

Until November 2024, only nine countries had sent declarations to the Secretary-General of IMO on their provisional applications for the 2009 amendment, pending entry into force. Among these countries, Norway and The Netherlands sent their declarations in 2020, Denmark, the Republic of Korea, the UK, Belgium and Sweden sent their declarations to IMO in 2022, while Switzerland and Australia sent their declarations in 2024.[3]



Legend

Green: Protocol Parties

Yellow: Convention Parties

Red: Non-Party States

Status as of December 2023

54 Parties to the London Protocol

87 Parties to the London Convention

10 Parties accepted the 2009 Amendment to Article 6

7 Parties sent a declaration on its provisional application of the 2009 amendment

Figure 1. Parties of London Convention 1972 and London Protocol 1996 [13]

The status of implementation of international regulations for CTS project countries is reported in *Table 1*.

Table 1. International Regulations for CTS countries

CTS Regions and Countries	**London Protocol (LP) & London Convention (LC)**	**Amendment to Article 6 of London Protocol (LP) and Letter of Provisional Application (LPA)**	**OSPAR Convention**
North Sea			
Denmark	Member of LP	LPA of Article 6 is submitted to IMO	Member of OSPAR
Norway	Member of LP	LPA of Article 6 is submitted to IMO	Member of OSPAR
Germany	Member of LP	Not implemented	Member of OSPAR

[13] International Maritime Organization (IMO). (2023). *Map of current LC/LP parties (December 2023)* [PDF]. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/LC_LP/Map%20of%20Parties%20(December%202023).pdf

CTS Regions and Countries	London Protocol (LP) & London Convention (LC)	Amendment to Article 6 of London Protocol (LP) and Letter of Provisional Application (LPA)	OSPAR Convention
France	Member of LP	Not implemented	Member of OSPAR
Belgium	Member of LP	Not implemented	Member of OSPAR
The Netherlands	Member of LP	LPA of Article 6 is submitted to IMO	Member of OSPAR
Baltic Sea			
Estonia	Member of LP	Amendment to Article 6 of LP implemented	Member on behalf of EU
Latvia	Not member	Not implemented	Member on behalf of EU
Lithuania	Not member	Not implemented	Member on behalf of EU
Black Sea			
Romania	Not member	Not implemented	Member on behalf of EU
Ukraine	Member of LC	Not implemented	Not member
Western Coast of Portugal			
Portugal	Member of LC	Not implemented	Member of OSPAR

3.1.3 OSPAR Convention

Convention for the Protection of the Marine Environment of the North-East Atlantic includes 15 countries on the western coasts and catchments of Europe and the EU, which cooperate to protect the marine environment of the NE Atlantic (Figure 2, Figure 3). OSPAR Convention was started with the Oslo Convention against dumping in 1972. It was extended in 1974 to include land-based sources and the offshore industry by the Paris Convention. The two conventions were unified, updated and broadened by the 1992 OSPAR Convention[14]. The new annexe on biodiversity and ecosystems was adopted in 1998 to cover non-polluting human activities that can adversely affect the sea[15]. The OSPAR Convention text was amended in 1998 and updated in 2002, 2005 and 2006. Amendments to Annexes II and III were adopted at OSPAR 2007.

[14] OSPAR Convention. (1992). *Convention for the Protection of the Marine Environment of the North-East Atlantic (with amendments)*. 33 pp. Retrieved from https://www.ospar.org/

[15] OSPAR Commission. (2018). *OSPAR Convention and its work*. Retrieved from https://www.ospar.org/.

Under the Rules of Procedure, the OSPAR Commission consists of representatives of each of its 16 Contracting Parties. The Contracting Parties are Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom, and the EU.

Annex II on the prevention and elimination of pollution by dumping or incineration includes Article 1, stating that it should not apply to any deliberate disposal in the maritime area of (a) wastes or other matter from offshore installations; (b) offshore installations and offshore pipelines; Article 2 (Incineration is prohibited) and Article 3:

Dumping all wastes or other matter is prohibited except those in paragraphs 2 and 3 of Article 3. This list consists of the following:

CO_2 streams from CO_2 capture processes for storage, provided that:

- disposal is into a sub-soil geological formation
- the streams consist only of CO_2 and may include incidental associated substances from the source material and the capture, transport and storage processes used
- no wastes or other matter are added for disposal
- they are intended to stay in these formations permanently and will not cause significant adverse consequences for the marine environment, human health and other legitimate uses of the marine area.

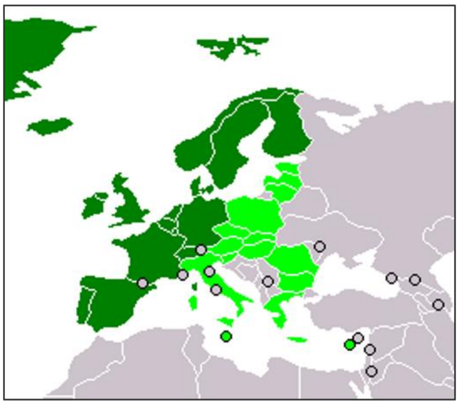


Figure 3. Parties of OSPAR Convention
Signatory states
European Union

Figure 2. OSPAR maritime area – the Arctic (I), the Greater North Sea II), the Celtic Seas, the Bay of Biscay/Golfe de Gascogne (III) and Iberian waters (IV), and the Wider Atlantic (V) www.ospar.org

3.2 Regional Regulations

3.2.1 Helsinki Convention

The Helsinki Convention seeks to protect the Baltic Sea Area's marine environment from all pollution sources[16]. It was initially adopted in 1974 with entry into force in 1980 but was later amended in 1992 following geopolitical developments and emerging environmental challenges in the region. The amended Convention entered into force in 2000. The Helsinki Convention has seven Annexes which

[16] HELCOM. (2024). *Convention on the Protection of the Baltic Sea Marine Environment*. Retrieved from https://helcom.fi/about-us/convention/

contain more detailed procedures, measures and regulations linked to the objectives, principles and obligations set out in the Convention.

The status of participation of CTS countries in regional conventions is reported in *Table 2*.

Table 2. Regional Regulations

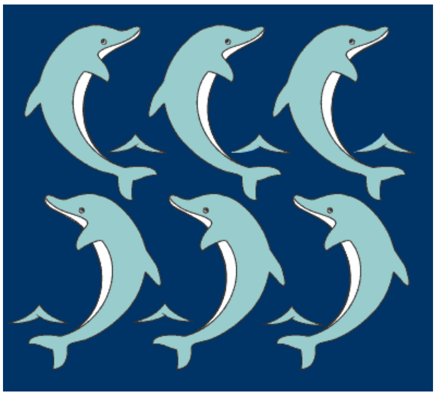
CTS Regions and Countries	**Helsinki Convention**	**Black Sea Convention**
North Sea		
Denmark	Member	NA
Norway	NA	NA
Baltic Sea		
Estonia	Member	NA
Latvia	Member	NA
Lithuania	Member	NA
Black Sea		
Romania	NA	Member
Ukraine	NA	Member
Western Coast of Portugal		
Portugal	NA	NA

Article 11 on dumping prevention prohibits dumping all wastes and other matter in the Convention area, except for dredged material. Dumping of dredged material requires, in each case, a prior special permit by the provisions of Annex V of the Protocol. This implies that storage of CO_2 is prohibited in the Baltic Sea Area. Any storage must, therefore, as of today, be onshore in the Baltic region. Onshore, there are no international conventions that directly regulate or ban the storage of CO_2; rather, this is regulated under the CCS Directive, which observes that it is the individual Member State's prerogative to decide whether to allow storage of CO_2 or not their territory (CCS Directive, Article 4). There are several countries in the Baltic region where onshore storage is either restricted (i.e., allowing only for R&D) or prohibited altogether.

For Denmark being a party to the OSPAR and Helsinki Convention (*Table 1*, *Table 2*), parts of the eastern continental shelf extend into the Baltic Sea and are regulated under the Helsinki Convention. Denmark's western, northern and parts of the eastern continental shelf fall within the OSPAR Convention, where storage is permitted. The Commission to the Helsinki Convention has clarified that the Convention is amended whenever necessary, such as following the developments in international environmental and maritime laws. This means that while storage is prohibited today, it may change in the future to follow the developments occurring under, e.g., the London Protocol and the OSPAR Convention.

The Contracting Parties to the Helsinki Convention included in CETP CTS project scenarios are Denmark, Estonia, Latvia and Lithuania (and the EU).

3.2.2 Black Sea Convention



The Convention on the Protection of the Black Sea Against Pollution, also known as the Bucharest Convention, does not yet include CO_2 storage regulations. The convention primarily focuses on preventing, reducing, and controlling pollution in the Black Sea, including pollution from hazardous substances, land-based sources, vessels, emergency situations, dumping, activities on the continental shelf, and the atmosphere. As such, the legality of offshore CO_2 storage practices in the Black Sea would likely be subject to international conventions and bordering countries' national laws. As the situation is very similar to that of HELCOM, CO_2 storage is not permitted now in the Black Sea.

The Commission on the Protection of the Black Sea Against Pollution (the Black Sea Commission or BSC), via its Permanent Secretariat, is the inter-governmental body established in implementation of the Convention on the Protection of the Black Sea Against Pollution (Bucharest Convention), its Protocols and the Strategic Action Plan for the Environmental Protection and Rehabilitation of the Black Sea (first Strategic Action Plan adopted in 1996 and titled "Strategic Action Plan for the Rehabilitation and Protection of the Black Sea " and the second titled " Strategic Action Plan for the Environmental Protection and Rehabilitation of the Black Sea" adopted in 2009)[17].

There are seven BSC Advisory Groups which provide their expertise and information support to the Commission and Secretariat in following sectors: (a) pollution monitoring and assessment; (b) control of pollution from land-based sources; (c) development of standard methodologies for integrated coastal zone management; (d) environmental safety aspects of shipping; (e) conservation of biological diversity; (f) environmental aspects of the management of fisheries and other marine living resources; and (g) information and data exchange.

Within the institutional framework coordinated by BSC, seven Black Sea Regional Activity Centres have been established based on existing national organisations.

BSC possesses cooperation links and options for consultative conversation with other intergovernmental organisations involved in marine pollution affairs at the global and regional level, including the United Nations Environment Program (UNEP), International Maritime Organization (IMO), Global Environmental Facility (GEF), International Commission for the Protection of the Danube River (ICPDR), Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS), Organization of the Black Sea Economic Cooperation (BSEC), European Environment Agency (EEA), different institutions of the European Union (EU) and some other organisations.
Romania and Ukraine are the Contracting Parties to the BSC included in the CETP CTS project (

Figure *4*).

[17] Black Sea Commission. (2024). *Convention for the Protection of the Black Sea Against Pollution*. Retrieved from http://www.blacksea-commission.org/_convention.asp

In the Black Sea region, a significant step towards carbon capture and storage has been taken with the ANRAV project[18]. This initiative, led by Heidelberg Materials, has secured €190 million from the EU Innovation Fund. The project is based in Varna, Bulgaria, and its primary goal is to store CO_2 under the bed of the Black Sea.

The ANRAV project represents this region's most recent development in offshore geological storage. It involves capturing carbon emissions from the Devnya cement plant in Bulgaria and transporting them for offshore permanent storage in the Black Sea.

The project is subject to regulatory and permitting aspects. It could start operations as early as 2028 if everything goes according to plan. Once operational, it is expected to have a capturing capacity of CO_2 of 800 kt/y. This project is a significant stride towards achieving carbon neutrality and reducing greenhouse gas emissions in the region.

Figure 4. Contracting Parties of the Black Sea Convention

3.3 Summary of National, Regional and International Regulations for the CTS Regions

There is a different regulatory situation for offshore CO_2 storage in four CTS sea regions. All needed regulations are implemented in the North Sea region countries (Norway and Denmark), and CO_2 storage export and import for offshore storage is permitted both at national and international levels (Table 3).

The situation is quite challenging in the Baltic Sea Region. CO_2 storage offshore Latvia is prohibited at national, regional and international levels. Latvia is not a member of the London Protocol (LP), and industrial CO_2 storage is not permitted by national regulations and by HELCOM in offshore geological structures. Estonia is a member of the London Protocol and has implemented an amendment to Article 6. However, this amendment is not yet in force. Lithuania is not a member of the LP, and any CO_2 injections are prohibited now in Lithuania.

[18] EC Innovation Fund. (2022). *ANRAV Project* (20 pp.). https://climate.ec.europa.eu/document/download/7eb6d2d5-c109-4c33-ba50-c065beb654d7_en?filename=if_pf_2022_anrav_en.pdf

In the Black Sea, the situation is different for Romania and Ukraine. Romania has implemented CCS regulations permitting CO_2 storage onshore and offshore. Therefore, storing it in national Romanian waters would be possible if the Black Sea Convention allowed it.

Ukraine has no CCS regulations; therefore, we can interpret that there is no regulatory basis for CO_2 storage in the geological structures in the Black Sea.

In the Western Coast of Portugal CTS scenario, CO_2 storage is permitted in national waters according to national regulations and OSPAR convention but not considered in the National Maritime Space Planning – Situation Plan. Approval of a spatial allocation plan is required before any activity. However, Portugal is not a member of the London Protocol and has not implemented related international regulations. Therefore, the export of CO_2 for storage offshore in Portugal is prohibited, but such an option is not planned in the CTS project (Table 3).

Table 3. The regulatory situation for offshore storage is *according to National CCS Regulations Regional conventions (HELCOM, Barcelona, Black Sea and OSPAR) and international regulations in the CTS Regions.*

	National and Regional Regulations	**International Regulations for offshore CO_2 storage (Amendment to Article 6 of London Protocol (LP))**
CTS Regions and Countries	**EU CCS Directive (national regulations for offshore storage) and regional conventions**	**CO_2 export and import for offshore storage is permitted internationally**
North Sea		
Denmark	CO_2 storage permitted	Permitted
Norway	CO_2 storage permitted	Permitted
Baltic Sea		
Estonia	CO_2 storage prohibited	Not permitted
Latvia	CO_2 storage prohibited	Not permitted
Lithuania	CO_2 storage prohibited	Not permitted
Black Sea		
Romania	CO_2 storage permitted by national CCS regulations	Not permitted
Ukraine	National CCS regulations are not available	Not permitted
Western Coast of Portugal		
Portugal	CO_2 storage is permitted but not considered in the National Maritime Space Planning – Situation Plan. Approval of a spatial allocation plan is required before any activity.	Not permitted

3.4 Regulatory recommendations for the CTS regions

As already mentioned in the previous subchapter, the situations in the four Sea Regions studied are different:

- Norway and Denmark have all the regulatory arrangements for offshore CO_2 transport and storage, including exports from third countries.
- To implement CTS technology, the Baltic Sea countries must change national CCS regulations in Latvia, HELCOM, implement an Amendment to Article 6 to the London Protocol by Latvia and Lithuania, and/or send Letters of Provisional Application (LPA) to IMO.
- In the Black Sea countries, national regulations are needed in Romania, while Ukraine must implement CCS regulations. The situation with the Black Sea Convention is not very clear. However, it does not include any CCS regulations (no binding, no permitting), and they must be implemented. (However, the CO_2 storage law (Emergency Government Ordinance 64/2011 transposed into Law 114/2013) from Romania also applies to the exclusive economic zone in the Black Sea).
- HELCOM (Helsinki Convention) and the Black Sea Convention need similar CCS regulations to be implemented as analogues to OSPAR CCS regulations.
- CO_2 storage in Portugal is permitted offshore for national CO_2 emissions according to national regulations and the OSPAR convention. However, extensive work is needed to regulate offshore activities necessary to implement offshore storage since the activity is not considered in the National Maritime Space Planning – Situation Plan. Thus, an Allocation Plan must be made before initiating any offshore storage activity.

Overall conclusions:

Among the four studied sea regions, one is already eligible and has all the necessary regulations (national, regional, and international for Denmark and Norway) to implement CTS technology – the Nordic region.

On the Western Coast of Portugal, CO_2 offshore storage is permitted, but an allocation plan to define the areas must be approved before any related offshore activity.

Another two CTS regions – Baltic and Black Sea regions- need changes in national and regional regulations, including a rising ban on CO_2 storage in Latvia, implementation of CCS regulations in Ukraine and CCS regulations by Helsinki and Black Sea Conventions.

4. North Sea Scenario

4.1 Introduction

The North Sea Scenarios incorporate three different sources of emissions:

- North European ports with known decarbonisation/CO_2 hub plans
- Local emitters in Norway
- Local emitters in Denmark

and two storage areas:

- The Danish North Sea sector has aquifers and abandoned/depleting hydrocarbon fields.
- The Offshore directorate mapped aquifers in the Norwegian North Sea southwestern sector. Abandoned or depleting hydrocarbon fields are not considered attractive storage sites and have not been the focus of storage licensing. Besides, Norway does not have pipelines from the offshore fields to the Norwegian mainland that are not in use. Therefore, reusing infrastructure for CCS is not a solution, as is the case in the UK and the Netherlands.

Figure 5. Key emitters, storage sites and ports in the North Sea Scenario.

A potential synergy with the Baltics scenario will be evaluated at later stages.

The scenarios compare today's standard solution with pipelines/shipping and offshore hubs vs. direct ship injection technology. The scenarios are set to directly compare the solutions and evaluate if direct ship injection can unlock the market for smaller/medium-sized emitters and be the most flexible and cost-effective solution in the build-up phase.

In Norway, the key emitters in the Southwestern area of the country were identified and mapped. The emitters are those with more than 40,000 tons of annual emissions (located very close to the larger ones, where infrastructure sharing is possible) and located along the fjords with easy ship access. Due to their geographical spread, standard storage value chains are unlikely to work for most emitters, and it is interesting to look at the possibility of direct ship injection becoming a market enabler. A similar approach has been used to identify local emitters in Denmark.

4.2 CO_2 emissions

Despite all the measures Norway took to reduce its footprint (see D5.1), industrial emissions to air[19,20] in 1990–2022 remain unchanged, see **Error! Reference source not found.**6. The primary emission sources are land-based industry, transport and offshore petroleum production.

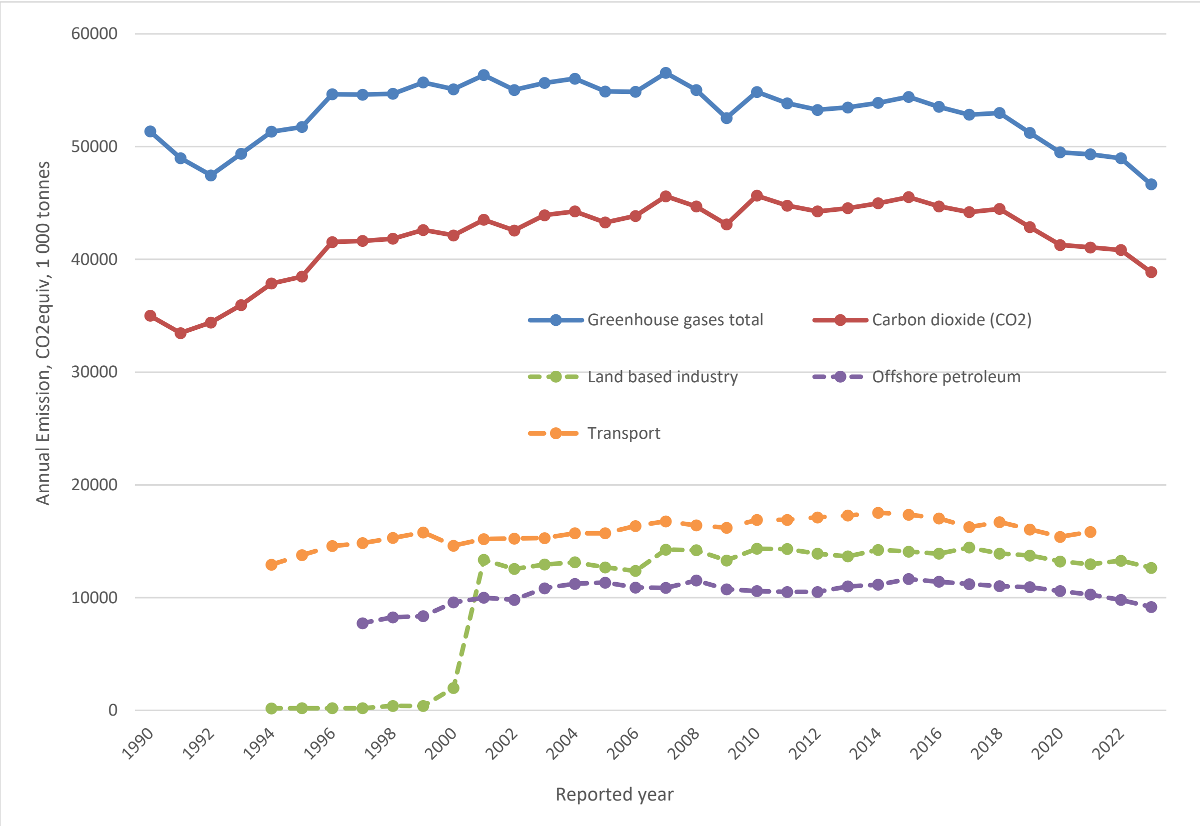


Figure 6. Total greenhouse emissions (blue solid line), total CO_2 emissions (solid red line), CO_2 emissions from transport (dashed orange line), land-based industry (dashed green line) and offshore petroleum production (dashed purple line) sectors for Norway.

Overall emissions selected for the Norwegian scenario are ca. 54% of all land-based emissions for 2023, constituting app. 6.6 Mtpa. The largest emitters among chosen with more than 0.5 Mt/y emissions are

[19] https://www.ssb.no/en/statbank/table/13931/tableViewLayout1/
[20] https://www.norskeutslipp.no/no/Forsiden/?SectorID=90

Mongstad Refinery (1.6 Mt/y in 2023), Yara factory in Prosgrunn (0.96 Mt/y), Gassco gas processing facility in Kårstø (0.73 M/y) and Heidelberg cement factory in Breivik (0.63 Mt/y).

Since 2006, Denmark has seen a significant reduction in its emissions, except for the trade and transport segment, as seen in Figure 77.

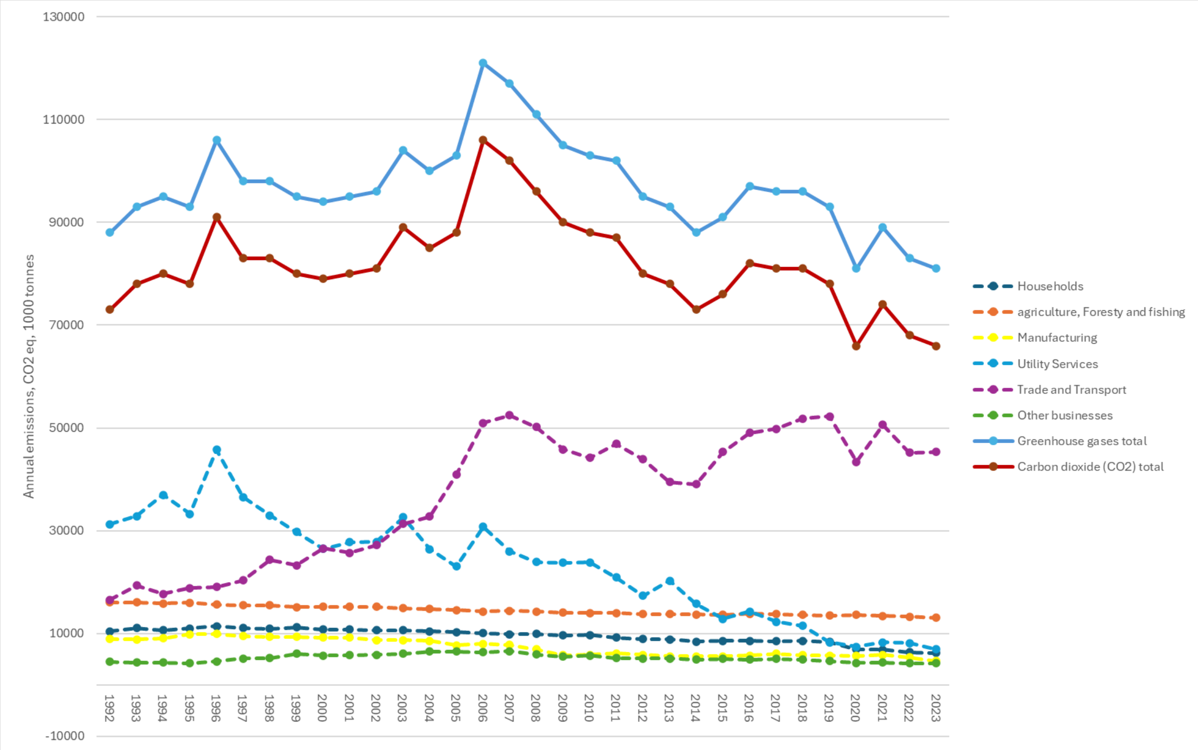


Figure 7. Total greenhouse emissions (blue solid line), total CO_2 emissions (solid red line), CO_2 emissions from transport (dashed purple line), and Utility Services (dashed blue line) sectors for Denmark. The international transport activities of Danish companies are included in the transport and total emissions section.

Emitters in both Denmark and Norway, with key parameters, are shown in Figure 1 and combined in **Error! Reference source not found.**4.

Table 4. Primary CO_2 Emitting Sources in Norway and Denmark reported for 2023.

	Facility Name	**Country**	**Industry Sector**	**EU ETS Permit ID[21]**	**CO_2 Reported (t/y)**
1	Aalborg Portland A/S	DK	Mineral	TCO2-7	1,979,482
2	Ørsted Bioenergy & Thermal Power A/S,Esbjergværket	DK	Energy	TCO2-990	1,322,885
3	Nordjyllandsværket	DK	Energy	TCO2-636	995,265
4	Ørsted Bioenergy & Thermal Power A/S, Studstrupvær	DK	Energy	TCO2-259	893,935

[21] https://www.euets.info/installations

	Facility Name	Country	Industry Sector	EU ETS Permit ID[21]	CO_2 Reported (t/y)
5	I/S Amager Ressourcecenter	DK	Energy/Waste	TCO2-244	555,250
6	Kalundborg Refinery A/S	DK	Energy/ Chemical	TCO2-1773	514,010
7	Fjernvarme Fyn Produktion A/S	DK	Energy	TCO2-251	501,345
8	Energnist, Energnist Esbjerg	DK	Energy	TCO2-1658	250,889
9	Nordværk I/S - Energianlægget Aalborg	DK	Energy/Waste Management	TCO2-263	220,130
10	Fortum Waste Solutions A/S	DK	Waste Management	IEPR-2023, Inspire ID: DK.CAED/000048306.SITE	171,000
11	Avedøreværket	DK	Energy	TCO2-269	162,358
12	Fjernvarme Fyn Affaldsenergi	DK	Energy/Waste Management	TCO2-1649	152,854
13	NLMK DanSteel A/S	DK	Metal production	TCO2-1729	116,493
14	Nordic Sugar A/S Nykøbing	DK	Food	TCO2-500	83,235
1	Mongstad Refinery	NO	Refinery	NO_92	1,670,350
2	Yara Porsgrunn	NO	Fertiliser production	NO_110	964,958
3	Heidelberg Materials	NO	Cement	NO_47	628,557
4	Kårstø Gassco	NO	Gas processing	NO_23	729,166
5	Hydro Aluminium Årdal	NO	Metall, Mineral products	NO_204083	450,930

	Facility Name	Country	Industry Sector	EU ETS Permit ID[21]	CO_2 Reported (t/y)
6	Hydro Aluminium Karmøy	NO	Aluminium	NO_204074	322,849
7	INEOS Rafnes	NO	Chemicals	NO_50	402,590
8	Eramet Norway Sauda	NO	Ferroalloys	NO_202628	340,876
9	Hydro Husnes	NO	Aluminium	NO_204082	233,587
10	Eramet Norway Kvinesdal	NO	Ferroalloys	NO_202529	220,539
11	Eramet Norway AS Porsgrunn	NO	Ferroalloys	NO_202608	121,199
12	Elkem AS Bjølvefossen	NO	Ferroalloys	NO_203890	135,936
13	Hydro Aluminium Høyanger	NO	Aluminium	NO_204072	107,912
14	INOVYN Norge	NO	Inorganic compounds	NO_36	87,274
15	Ineos Bamble AS	NO	Plastic	NO_35	12,677
16	Speira Karmøy	NO	Aluminium	NO_216841	13,056
	Total CO_2 emissions	NO			6,442,456
	Total CO_2 emissions	DK			7,919,131
	Total CO_2 emissions in Norway and Denmark				14,361,587

4.3 CO_2 Storage Sites

As mentioned, Norway's current licensing policy for CO2 storage does not allow carbon dioxide storage in abandoned or depleting hydrocarbon fields. Therefore, the key aquifers in the southwest of Norway have been selected as potential storage sites. It is important to state that:

- Mapped aquifers, not licences, are considered; see Figure 8. This is done to avoid issues with pore space or pressure space sharing and to avoid limiting storage potential to existing licences. Current practice in Norway allows operators to nominate areas of interest for licensing. The 11 licences granted as of 01.01.2025 have not officially reported their expected volumes.
- Effective storage capacity is taken from offshore storage directorate atlases[22] or other public sources. According to the methodology presented in the atlases and approach of the EU Geocapacity project was used.
- Different formations may geographically overlap as they are located at different depths.

[22] CO_2 atlas for the Norwegian Continental Shelf. CO_2 atlas for the Norwegian Continental Shelf - The Norwegian Offshore Directorate

- The selection of areas for CO_2 permanent storage in the Danish part of the North Sea is based on a combination of geological, environmental, and practical considerations to ensure safe and efficient long-term storage. The North Sea's abundant deep saline aquifers provide an excellent foundation for CO_2 storage due to its extensive capacity, impermeable cap rock layers, and geological stability. Additionally, detailed studies have been conducted on near-coastal areas such as Lisa, Jammerbugt and Inez. Among these, Jammerbugt stands out for its significantly higher storage capacity potential, making it an up-and-coming option. Although Lisa and Inez possess lower capacities, they remain viable alternatives for regional storage needs.
- Depleted oil and gas fields in the Danish sector of the North Sea also present compelling opportunities for CO_2 storage, as these sites have a proven ability to contain fluids securely over geological timeframes. Fields nearing or having recently ceased production (Close Cease of Production, COP) are especially attractive because they reduce operational conflicts and can utilise existing infrastructure. Factors such as suitability, the absence of numerous legacy wells (which decreases the risk of leakage), and adequate storage capacity are critical in selecting these fields. Based on these criteria, four candidate fields—Greensand, Harald, Roar, Halfdan and Kraka—have been identified as candidate sites for permanent CO_2 storage due to their geological suitability, minimal risk of leakage, and favourable capacity. As part of Denmark's CCS strategy, projects like Project Greensand aim to utilise such fields. For example, the depleted Nini West field, part of the Project Greensand initiative, demonstrated CO_2 storage in March 2023, marking a significant milestone in CCS development.

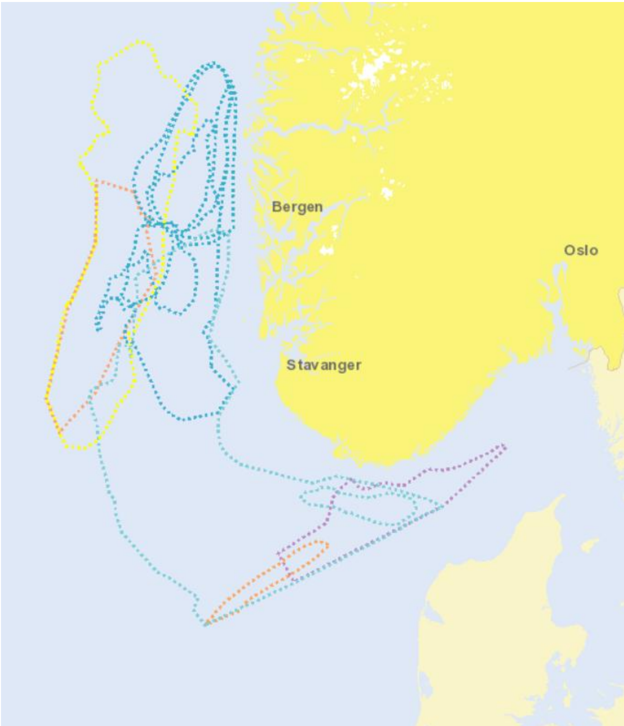


Figure 8. Storage formations in the Norwegian North Sea[23].

[23] https://sodir.maps.arcgis.com/apps/webappviewer/index.html?id=663ebb1c3c5241db935bc751254c9578

The key data for North Sea scenario storage options is gathered in Table 5. Details for geological structures and capacity assessments may be found in the Norwegian Offshore Directorate Storage atlas[24].

Table 5. Key parameters and estimated storage capacity for key formations in Norway and storage sites in Denmark.

Formation name	Country	Depth, m	Permeability, mD	Porosity, %	Storage capacity, Mt
Utsira and Skade	NO	900–1300	1000	21	500–1 500
Bryne and Sandnes	NO	1700–2000	150	9	500–2 000
Sognefjord[25]	NO	1750–1950	300	18	Up to 4000
Johansen and Cook	NO	1750–1900	400	15	150
Statfjord[24]	NO	2400	200	11	Up to 800
Gassum and Skagerak[24]	NO	600–720	450	12	Up to 600
Stord, Hugin East	NO	1700–1800	500	13	50
Fiskebank[25]	NO		1000	25	200
Jammerbugt[26]	DK	1600	500	20	199
Inez[27]	DK	1660	400	25	178
Lisa[27]	DK	1720	400	25	29
Greensand[27]	DK	2060	100	25	178
Harald[28]	DK	2700	0.2	15	40
Roar[28]	DK	2025	0.6	20	48.5
Kraka[28]	DK	1800	0.4	25	11
Hafdan[28]	DK	2100	1	25	83.5

Project Greensand (Nini West is the pilot) has been licensed in Denmark, with INEOS serving as the operator. The Harald gas field has been licensed for CO_2 storage, and Total Energies is the Operator. The Jammerbugt, Inez, and Lisa areas have been opened for tendering for CO_2 storage licenses.

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[24] https://www.sodir.no/en/whats-new/publications/co2-atlases/co2-atlas-for-the-norwegian-continental-shelf/

[25] Here storage atlas provides only Capacity of 22 Gt, not prospectivity. We choose to take 0.2 storage efficiency like in GeoCapacity project

[26] Michael B.W. Fyhn, Anders Mathiesen, Egon Nørmark, Finn Mørk, Florian Smit, Henrik Vosgerau, Shahjahan Laghari, Thomas Funck, Tomi Jusri & Ulrik Gregersen. CCS2022-2024 WP1: The Jammerbugt Structure. GEUS Report 2024/11.

[27] Shogenova A., Shogenov K., Gravaud I., Sousa L., Wójcicki A., Lothe A.E., da Silva E. F., Sınayuç C., Yıldırım B., Bülbül S., Schmitt F., Honegger M., Ombudstvedt I., Østgaard L., Frykman P., Bouvier L., Perimenis A., Karimi F., Marzban E., Lopez A. (2025). A generic framework for selection of the most promising CCUS value chains. CCUS ZEN project D3.3 Report, 78 pp.

[28] M. Bonto, M.J. Welch, M. Lüthje, S.I. Andersen, M.J. Veshareh, F. Amour, A. Afrough, R. Mokhtari, M.R. Hajiab adi, M.R. Alizadeh, C.N. Larsen, H.M. Nick. Challenges and enablers for large-scale CO2 storage in chalk formations. *Earth-Science Reviews* 222 (2021), https://doi.org/10.1016/j.earscirev.2021.103826

4.4 CO_2 Transport

In the standard approach scenario, CO_2 will be delivered from selected EU ports by ships to a central hub at Draupner; see Table 6 for distances and sailing times. Further from the Draupner hub, CO_2 will be transported by short-distance pipelines to subsurface injection equipment.

Several alternatives to the Draupner hub are envisioned, including transport to the South (Egersund) and North (Utsira) formations in the Norwegian North Sea and three storage locations in Denmark. The same routes can be used for direct ship injection to compare the TEA parameters to standard scenarios with ships used only for transport.

In Denmark, Harald could serve as a hub for CO_2 storage not only because it is licensed for CO_2 storage (Bifrost Project EUDP) but also due to its proximity to other depleted or soon-to-be-depleted fields that could be repurposed for CCS. Additionally, its connection to Danish and European gas pipelines enhances its strategic importance for large-scale CO_2 transportation and storage (Fig.8).

In Norway, emitters are selected along the fjords, and the ships are expected to pick up carbon dioxide directly from the emitters. Minor aggregations, i.e. short-distance transport, may be expected in some locations. Pipelines or truck transport will be considered.

In the same way, in Denmark, large emitters near coastal lines with potential facilities to accept ships were selected. The assumption is that CO_2 will be collected directly by ships, while pipelines or truck transport will also be considered.

In Denmark, an available gas pipeline is planned to connect to the Esbjerg port via the Nybro redelivery point as part of an ongoing CO_2 delivery project by Ørsted. If the pipeline is repurposed, other emitters located far from the shore and not selected for CTS scenarios can transport CO_2 via the pipeline.

4.4.1 Ports

Four North Sea ports are included in the North European part of the scenario:

- Wilhelmshavn – a CO_2nnectNow project with an estimated capacity of 10 Mt/y CO_2[29]
- Dunkerque – a concrete plan with 1.5 Mt/y CO_2 AirLiquid project[30] annual capacity and "additional capacity could be considered[31].
- Zeebrugge (port of Antwerp-Bruge) – Fluxys and Equinor are working on a 20–40 Mt/y CO_2 capacity, 1000 km open-access pipeline from Zeebrugge to the North Sea[32,33]
- Emshaven. RWE is planning a collection site for CO_2 with a capacity of up to 9–11 Mt/y. No current plans have been found for Emden, which is located in the same area. However, natural gas handling capacity through the terminal is 34.1 million m^3 CO_2 per day[34].

[29] https://wintershalldea.com/en/newsroom/wintershall-dea-and-hes-wilhelmshaven-tank-terminal-intend-jointly-develop-co2-hub-wilhelmshaven
[30] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/projects-details/43251567/101147522/CEF2027
[31] https://dunkerquelenergiecreative.fr/en/news/7-dunkirks-co2-hub-the-first-co2-hub-in-france/
[32] https://www.fluxys.com/en/projects/zeebrugge-offshore-co2-pipeline
[33] https://www.equinor.com/news/fluxys-and-equinor-launch-solution-large-scale-decarbonisation
[34] https://www.offshore-technology.com/news/newsnorways-gassco-opens-new-gas-receiving-facility-emden-germany-4903462/?cf-view

The Eisberg, Kalundborg and Copenhagen ports will be applied to transport emissions from West, Center and East Danish CO_2 clusters in Denmark. One notable initiative is Ørsted's carbon capture project, which began construction in December 2023. This project involves capturing CO_2 from the Asnæs Power Station in Kalundborg and the Avedøre Power Station near Copenhagen. The captured CO_2 will initially be transported by truck from Avedøre to Asnæs, where it will be temporarily stored.

Subsequently, the CO_2 will be shipped to Norway's Northern Lights storage facility for permanent sequestration. The project aims to capture 430,000 t/y of biogenic CO_2, contributing significantly to Denmark's climate targets for 2025 and 2030.

Esbjerg (SJ): CO_2 is received at the terminal in port (260 km) and transported via existing pipeline or ship to Harald, Halfdan, Roar, and Kraka Gas fields.

In Norway, as described in the previous chapter, the key facilities where CO_2 will be picked up are Mongstad in the Northern cluster, Husnes in the central one, Kårstø in the Southern and Herøya in the Eastern.

4.4.2 Shipping Routes

The main shipping routes for conventional shipping to the hub are shown in Figure 99 in black, with routes to the Egersund formation area in blue and the Utsira formation area in red. The Egersund and Utsira areas represent South and North locations selected for evaluating the costs of infrastructure and shipping distance needed. Similarly, Figure 1010 presents potential shipping routes to 3 locations in the Danish sector of the North Sea. The red lines indicate the route to the Harald Hub, which is located near depleted oil and gas fields.

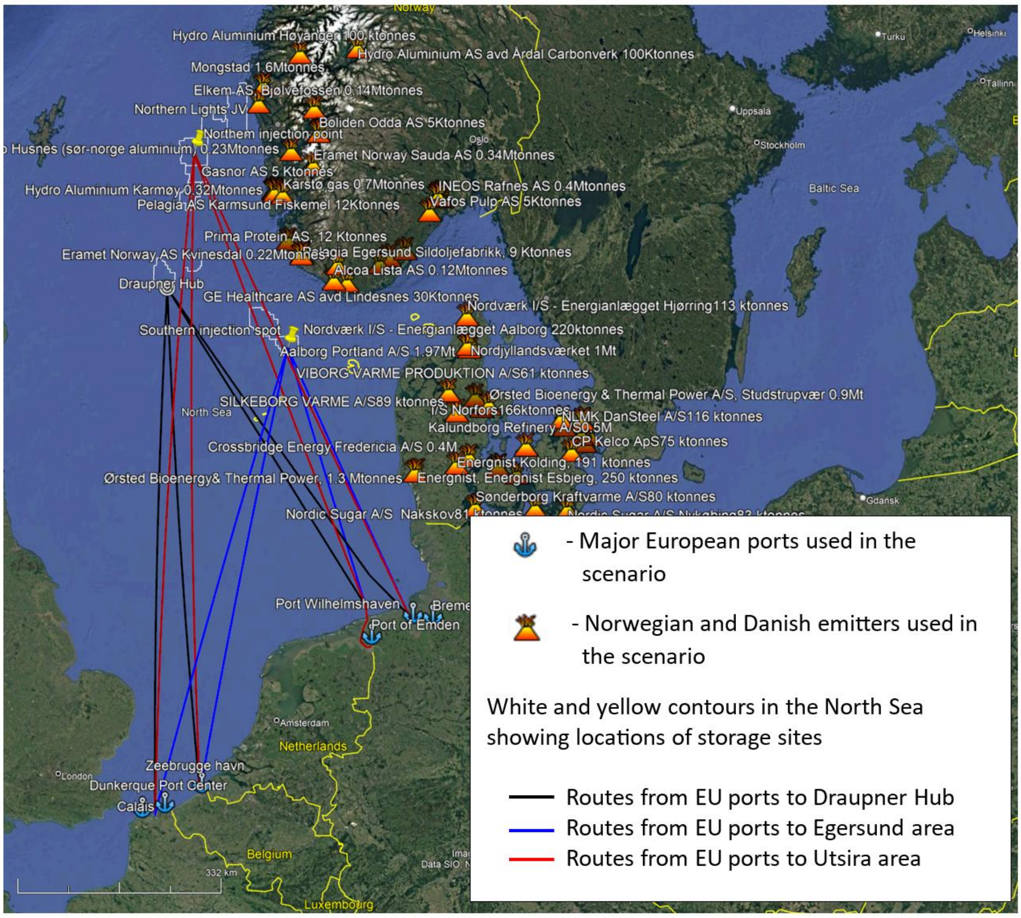


Figure 9. Shipping routes alternatives from EU ports to Norwegian North Sea storage locations.

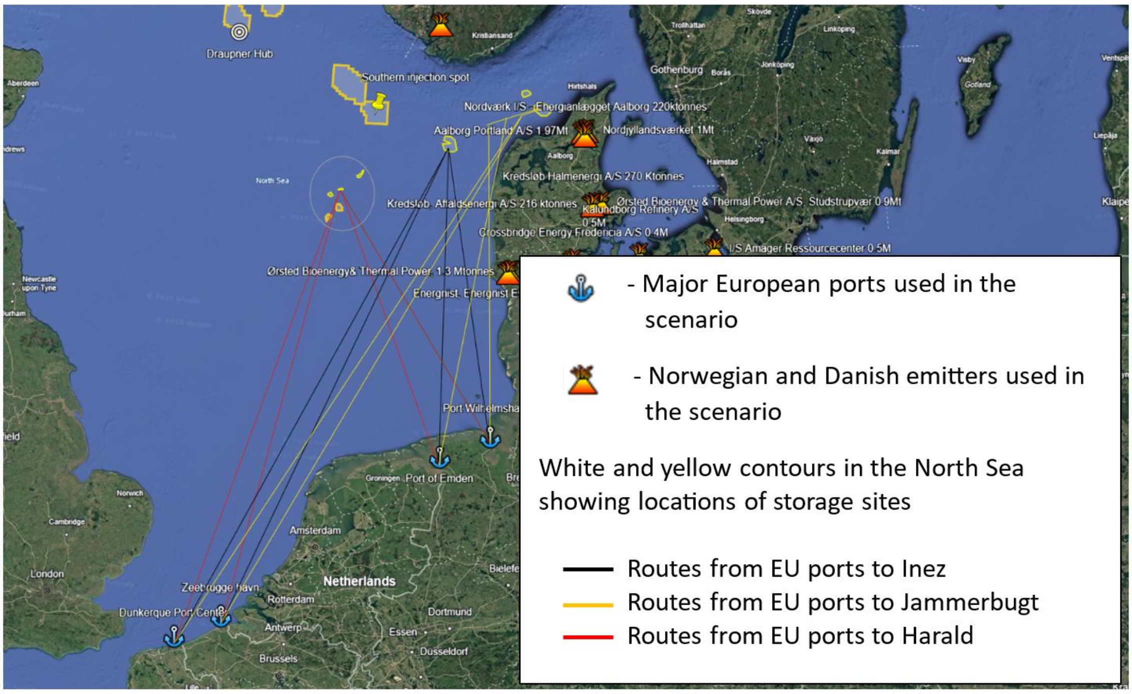


Figure 10. Shipping route alternatives from EU ports to Danish North Sea storage locations.

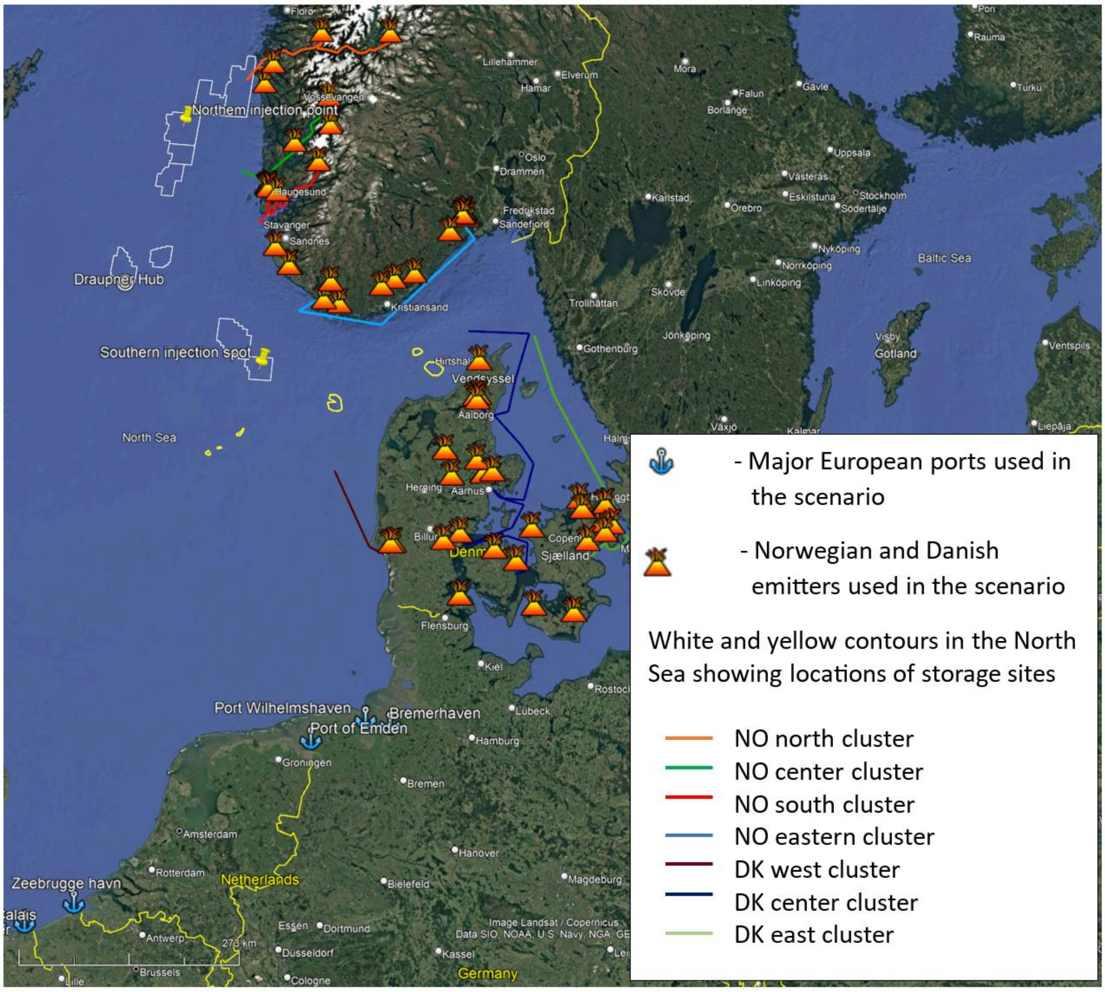


Figure 11. Potential shipping routes for local emitters in Denmark (Western cluster – dark red route, Central cluster in blue and Eastern in green) and Norway (Eastern in light blue, southern in red, central in green, northern in orange).

Regarding local Norwegian and Danish emissions, several shipping routes are envisioned. Generally, if grouping all emitters by their locations, four routes may be identified in Norway, as shown in Figure 1111 in blue, red, green and orange and three in Denmark (dark red, dark blue and green). The Danish eastern route (green) may also be combined with the delivery of CO_2 from the Baltic region.

The scenario will have to evaluate if several routes can be serviced by the same ship, how large the ships should be and if all emitters identified so far should be included.

The potential shipping routes from EU ports to storage locations are summarised in Table 66, with base case scenario one shown in bold. We assume the average speed of a vessel is ca. 13 knots or approximately 25 km/h.

Table 6. Shipping routes from European ports to different storage hubs/locations.

Route	**Distance, km (nautical miles)**	**Sailing time, h**
Wilhelmshaven–Draupner Hub	624 (337)	25
Emshaven–Draupner Hub	637 (344)	25
Zeebrugge–Draupner Hub	763 (412)	29
Dunkerque–Draupner Hub	801 (432)	32
Wilhelmshaven–South (Egersund)	448 (242)	18
Emshaven–South (Egersund)	475 (256)	19
Zeebrugge–South (Egersund)	686 (370)	27
Dunkerque–South (Egersund)	741 (400)	29
Wilhelmshaven–North (Utsira)	783 (423)	31
Emshaven–North (Utsira)	806 (435)	32
Zeebrugge–North (Utsira)	970 (524)	39
Dunkerque–North (Utsira)	1009 (545)	40
Wilhelmshaven–Jammerbugt	465 (251)	18
Emshaven–Jammerbugt	495 (267)	20
Zeebrugge–Jammerbugt	791(427)	31
Dankerque–Jammerbugt	839 (453)	33
Wilhelmshaven–Inez	385 (207)	15
Emshaven–Inez	406 (219)	16
Zeebrugge–Inez	679 (366)	27
Dankerque–Inez	732 (395)	29
Wilhelmshaven–Harald	379 (204)	15
Emshaven–Harald	374 (201)	15
Zeebrugge–Harald	577 (311)	23
Dankerque–Harald	628 (399)	25

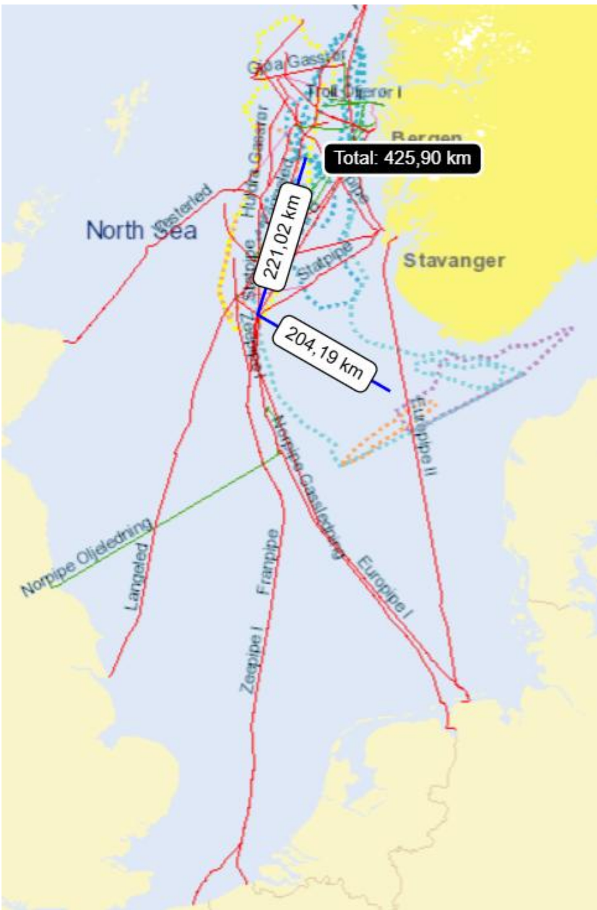
In addition, the following is assumed:

- Loading capacity at port: 1350 tons per hour
- Required additional time at port 4 hours
- Required additional time at unloading location 4 hours
- Unloading time will depend on a number of wells and their injectivity

4.4.3 Pipeline Routes

Several natural gas pipelines, presented in Figure 1212, may be relevant for the project from the perspective of either reversing them for CO_2 transport or using them as potential corridors for new CO_2 pipelines[35]:

- Europipe II is a 658 km long pipeline connecting Dornum to Kårstø. 42 inches at 24 billion m^3 annual capacity.
- Europipe I a 620 km long pipeline connecting Dornum and Emden to Draupner SE platform. 40 inches with 18 billion m^3 annual capacity.
- Norpipe is a 440 km long pipeline connecting Ekofisk field to Emden. 36-inch pipeline with 16 billion m^3 annual capacity.
- Zeepipe is a pipeline connecting Troll via Kollsnes (Kvitebjørn, 147 km, 30 inches, 10 billion m^3 annual) to Draupner and Sleipner (each 300 km, 40 inches, 26 billion m^3 annual capacity). Sleipner and Draupner are linked by 30 km, 40 inches 26 billion m^3 annually. Zeepipe is 814 km from Draupner to Zeebrugge, with 40 inches and 15 billion m^3 annual capacities.
- Franpipe is Draupner E to Dunkerque, an 840 km, 42 inch, 19.6 billion m^3 annual capacity pipeline.
- 105-km, 32-inch branch pipeline connecting Europipe II with the Danish mainland (Figure 1313).



[35] https://map.gassco.eu/map

Figure 12. Existing gas pipelines (in red) and potentially needed (in blue) from the hub to northern and southern injection points.

So far, the hub has been placed at the Draupner location where Franpipe, Zeepipe and Europipe I lead. If the alternative location to the hub illustrated in Figure 13 is chosen, the overall length of required pipelines to the Northern and southernmost injection points will remain largely the same. The possibility of connecting the hub to the Danish storage site may also be considered if the scenario with shorter connections in Norway will prove to be economical.

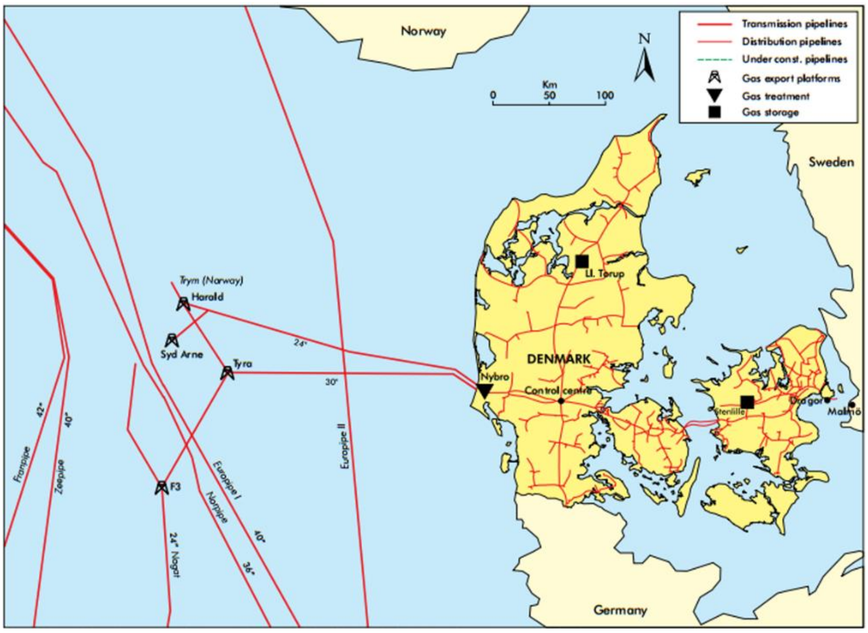


Figure 13. Existing Danish gas pipelines in the North Sea and their connection to the European pipeline network.

4.7 CO_2 Use

There are no concrete industrial-scale plans for CO_2 usage in Norway. Therefore, utilisation is not evaluated in current scenarios.

In Denmark, Power to X projects are in operation and under discussion. The CO_2 demand from these projects could amount to ~0.3 Mt/y by 2030 and ~0.6 Mt/y by 2035.

4.8 Summary

The North Sea Scenario comprises selected Danish and Norwegian emitters and storage sites. Other emission sources and storage sites exist in both countries. Selection is based on criteria developed specifically for the CTS project.

In the Danish part of the North Sea, selected major local emitters near the coastline can utilize three possible routes for CO_2 collection, with ships transporting it for direct injection. Three storage sites have been identified: depleted hydrocarbon fields around the Harald Hub, Jammerbugt, and the Inez saline aquifers. The selected hub is connected to the Danish and European gas pipeline network but not to the selected saline aquifers.

Overall, the scenario will consider storing up to 7.5 Mt/y emissions from Denmark, 6.1 Mt/y from Norway and 40–60 Mt/y from European ports.

The longest possible transport route is 1000 km or 540 nautical miles between Dunkerque and Utsira formation storage area in the Northern part of the Norwegian North Sea.

The total estimated CO_2 storage capacity is 2.5–5 Gt in Norway and around 0.3–0.4 Gt in Denmark, providing a scale of 20–80 years of mapped emissions.

Table 7 Danish and Norwegian emitters and storage sites.

Cluster*	**Emissions**		**Distance**		**Storage**	
	Reported, t/y	**For storage** * Mt/y**	**to port***, km**	**to site, km**	**Site**	**Capacity, Mt**
DK west (Eisberg), 2 emitters	1,573,774	1.5	4	200	Inez	
DK center (Kalunborg) 9 emitters	5,511,256	5.2	35	700	Jammerbugt /Lisa	>200
DK east (Copenhagen) 3 emitters	834,101	0.8	60	600		
NO north (Mongstad) 3 emitters	2,229,192	2.1	0	350	Johansen and Cook****	150
NO center (Husnes) 2 emitters	369,523	0.35	0	300	Hugin****	50
NO south (Kårstø) 4 emitters	1,405,947	1.3	0	350		
NO east (Herøya) 7 emitters	2,437,794	2.3	5	460	Gassum-	600
Wilhelmshavn		10	0	450	Bryne, Fiskebank, Gassum	3000
Dunkerque		1.5	0	800	Utsira, Sognefjord	>4000
Zeebrugge		20–40	0	760	Utsira, Sognefjord	> 4000
Emshaven		9–11	0	475	Bryne, Fiskebank, Gassum	3000
	TOTAL:	54–76	105	5445	TOTAL:	4300–

						9300

* As shown in Figure 11.
**Assuming app 95% capture
*** 0 means pick up of CO_2 by the ship on site.
**** can also be injected into Utsira, subject to TEA
- can also be injected into Bryne / Sandnes, subject to TEA

Three realisations of the North Sea scenarios include:

Scenario I. Ship transport from EU ports to two hubs. The potential to re-use existing gas pipelines will be considered. CO_2 is further distributed from offshore hubs to the sites using pipelines and subsurface injection equipment.

Scenario II. This is an exact copy of scenario I with direct ship injection replacing the hub, pipelines, and subsurface injection infrastructure to compare the efficiency of direct ship injection technology directly to that of fixed infrastructure.

Scenario III is based on Scenario II, adding emitters in Denmark and Norway to evaluate if direct ship injection technology can function as an enabler for smaller emitters in the region.

5. Baltic Sea Scenario

5.1 Introduction

The Baltic scenario encompasses CO_2 emissions from Estonia, Latvia, and Lithuania, with CO_2 storage planned in the E6 structure offshore Latvia (Figure 14).

All three countries submitted their draft National Energy and Climate Plans (NECP) for 2021–2030 to the European Commission (EC) in 2023. Latvia finalised its NECP in the summer of 2024, and Lithuania submitted its final NECP in October 2024[36].

Each country aims to achieve climate neutrality by 2050. Despite their ambitious climate goals, Estonia, Latvia and Lithuania did not include CCS plans in their draft NECPs 2023. The EC recommended that these countries: 1) identify the annual CO_2 capture potential by 2030, including sources such as biogenic emissions or direct air capture; 2) detail the transportation methods and infrastructure for captured CO_2; and 3) specify the CO_2 storage capacity and injection volumes available by 2030[37,38,39].

In its final plan for 2024, Latvia[40] did not plan any policy measures in CCUS. It answered to EC that "1) by 2030, there will be no carbon capture in Latvia and therefore there will be no storage, transport or reuse of captured carbon, 2) the single natural gas transmission and storage system operator shall plan to carry out a project to assess the storage potential of captured carbon in the natural gas storage facility."

Lithuania reported plans for CO_2 capture, transport and utilisation but not for CO_2 storage. The Lithuanian policy measures to implement CCUS technologies include 1) deployment of carbon capture technologies with priority for biogenic carbon capture and atmospheric CO_2, which can then be used to produce synthetic energy products or transfer to permanent storage with negative emissions (2024–2050); 2) establishment of CO_2 transport infrastructure, dedicated to both the export of fossil CO_2 and the import of biogenic CO_2 that local actors will use as feedstock to produce synthetic fuels(2024–2030); 3) establishing a carbon recovery market and developing its potential, including development of standards and market conditions for synthetic products produced using H_2 and CO_2 (2025-2030); 4) establishment of a CO_2 monitoring system.

The Lithuanian plan[41] includes some predictive numbers for captured CO_2 emissions (fossil CO_2 - 2.4 Mt/y by 2040 and 1 Mt/y by 2050, biogenic CO_2 - 0.2 Mt/y by 2030, 3.5 Mt/y by 2040 and 3.5 Mt/y by 2050) and for used and transported CO_2. Geological CO_2 storage in Lithuania is not planned in the report. All produced biogenic CO_2 is planned for CO_2 utilisation.

Industrial companies in Latvia, including Latvenergo and Schwenk Cement Latvia, and those in Lithuania, are discussing with their governments regarding CO_2 storage regulations. Estonia, Latvia, and Lithuania have a history of close regional cooperation in energy, exemplified by shared use of the Inčukalns Underground Gas Storage (UGS) facility, joint energy systems, the Rail Baltica project, and

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[36]EC. (2024). N*ational energy and climate plans 2021–2030*. National energy and climate plans

[37] EC. (2023). *Commission recommendation, assessment (SWD) and factsheet of the draft updated national energy and climate plan of Lithuania*. 9pp.

[38] EC. (2023). *Commission recommendation, assessment (SWD) and factsheet of the draft updated national energy and climate plan of Estonia*. 10pp.

[39] EC. (2024). *Commission recommendation, assessment (SWD) and factsheet of the draft updated national energy and climate plan of Latvia*. 7pp.

[40] Ministry of Climate and Energy of Latvia. (2024). *Latvia - Final updated NECP 2021-2030,* 135 pp. and 4 annexes.

[41] Ministry of Energy of the Republic of Lithuania. (2024). *Lithuania - Final updated NECP 2021–2030,* 423 pp.

various intergovernmental councils and plans such as the Baltic Assembly, the Baltic Council of Ministers (BCM), and the Baltic Energy Market Interconnection Plan (BEMIP).

The EU CCS Directive was implemented in the Baltic states in 2011. At that time, CO_2 storage was banned in Estonia and Latvia, except for research purposes involving less than 100,000 tons of CO_2. CO_2 transportation is permitted in both countries. Although the Latvian ministry is considering regulatory changes, the current regulations remain unchanged[42,43]. In contrast, Lithuania permitted CO_2 storage both onshore and offshore until 2019, when the agricultural party leading the government decided to ban underground CO_2 injection, effective from 2020. Despite efforts by Lithuanian cement plants owned by Schwenk to communicate and disseminate information, no regulatory changes are anticipated. Latvia is considered to have the best geological conditions for CO_2 storage in Europe, with low reservoir temperatures allowing for dense CO_2 phases in onshore structures. Consequently, Latvia, supported by industrial activities from companies like Latvenergo and Schwenk Latvia, is the only Baltic country with viable prospects for CO_2 storage.

5.2 CO_2 emissions: Decarbonisation and CO_2 Management in the Baltic States

The Baltic scenario includes major CO_2 emitters from Estonia, Latvia, and Lithuania, located mainly near ports for efficient transport and storage of emissions in the E6 structure offshore Latvia. Estonia, Latvia, and Lithuania are small countries in north-eastern Europe. The smallest Estonia has a population of less than 1.4 million and an area of 45,335 km². Latvia and Lithuania are more extensive, with areas of 64,589 km² and 65,300 km² and populations of 1.9 million and 2.88 million, respectively. In 2023, Estonia's total GHG emissions were 14.36 Mt CO_2eq, Latvia's were 10.96 Mt CO_2eq, and Lithuania's were 20.68 Mt CO_2eq.[44] CO_2 emissions per capita were highest in Estonia due to its reliance on oil shale for energy and shale oil production. These emissions are concentrated in north-eastern Estonia, where oil shale deposits and major CO_2 producers are located. Additional significant three emitters are near Tallinn, producing mainly bio-CO_2 emissions.

In Latvia, the largest CO_2 emitters are in Riga, the capital with a population of 0.6 million, and the western part of the country. Riga Port, the largest in Latvia and the second biggest in the Baltic region handles a variety of cargo and was selected to manage CO_2 emissions from Latvenergo power plants.[45]

In Estonia, the major fossil CO_2 emitters in the NE Estonia (Ida Viru) include Enefit's Auvere Power Plant and Shale Oil Plant, VKG's Energia North Thermal Plant and Shale Oil Plant and Kiviõli Chemical Plant and mainly bio-CO_2 emitters located near Tallinn - Horizon Paper Factory, Utilitas Tallinn Power Plant, and Iru waste-to-energy plant with significant emissions from both power and industrial sectors, totalling approximately 3,918,626 tons of CO_2 in 2023.

Latvia's largest emitters are Latvenergo's Tec-1 and Tec-2 power plants and Schwenk Latvia's cement plant, all planning CO_2 capture initiatives, with total emissions of around 1,444,499 tons of CO_2 in 2023. In Lithuania, the key emitters are Orlen Lietuva's refinery, Gren Klaipėda's waste-to-energy plant, Akmenės Cement, UAB Kauno's waste-to-energy plant, and Achema's chemical production, contributing substantial emissions from energy, cement, and chemical sectors, with a total of

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[42] Shogenova, A., Piessens, K., Ivask, J., Shogenov, K., Martínez, R., Flornes, K., Poulsen, N., Wójcicki, A., Sliaupa, S., Kucharič, L., Dudu, A., Persoglia, S., Holloway, S., & Saftic, B. (2013). CCS directive transposition into national laws in Europe: Progress and problems by the end of 2011. *Energy Procedia, 37*, 7723–7731. https://doi.org/10.1016/j.egypro.2013.06.718

[43] Grasmane, A. (2023). Latvia's climate policy. *Ministry of Climate and Energy, Republic of Latvia*. Baltic Carbon Forum - 2023.

[44] EC. (2024). *EDGAR report 2024*. https://edgar.jrc.ec.europa.eu/report_2024.

[45] Riga Freeport Authority. (2024). *Port location*. https://rop.lv/en/port-location

approximately 4,013,316 tons of CO_2 in 2023. Further details are given for each country below (Table 8, Table 9, Table 10).

In January 2025, Lithuania proposed to discuss the construction of a new Baltic Power Plant shared by three countries, and this plant will not be nuclear.

5.2.1 Estonia

Emitters included in the Baltic scenario are owned by the national Estonian company Enefit (Eesti Energia). Enefit owns Auvere PP, which uses oil shale and bio-waste for energy production, Auvere Shale Oil Plant and Iru waste for energy plant (Table 8). Auvere PP was built in 2015, and Estonia plans to save it in working conditions for baseload energy production. The largest in Estonia, Eesti and Baltic PPs close to Auvere in NE Estonia, will probably be closed by 2027–2030 (Baltic PP is already closed) and replaced by renewable energy production.

Table 8. Emitters from Estonia included in the Baltic Scenario[46,47]

Num-ber	EU ETS ID of the plant	Plant Name	Region/Town	Sector	Fossil CO_2 2023, t/yr	Bio CO_2 2023, t/yr	CO_2 emissions 2023, t/yr
1	KKL-324417	Auvere PP	Ida-Viru /Auvere	Power	681,162	256,035	937,197
2	KKL-176540	Auvere SOP	Ida-Viru /Auvere	Shale Oil Plant	975,506		975,506
3	KKL-300389	VKG SOP	Ida-Viru /Kohtla-Järve	Shale Oil Plant	721,077		721,077
4	L-KKL-IV-204118	VKG Energia North TP	Ida-Viru /Kohtla-Järve	Power	619,974		619,974
5	L-KKL-IV-171223	Kiviõli Chemical Plant	Ida-Viru/ Kiviõli	Shale Oil Plant	231,536		231,536
6	L-KKL-HA-217188	Horizon Paper Factory	Harju/Kehra	Paper	4030	121,311	125,341
7	L-KKL-HA-162843	Utilitas Tallinn PP	Harju/Tallinn	Power	49	156,170	156,219
8	L-KKL-HA-222658	Iru WtEP	Mardu/Iru	WtE	1835	149,941	151,776
	Total CO_2 emissions 2023				**3,235,169**	**683,457**	**3,918,626**

Estonia plans to build a new gas power plant, working on hydrogen, biogas and partly natural gas power plants instead of Enefit oil shale plants to provide baseload energy. The possibility of building a small nuclear power plant for the new generations is seriously considered by Estonian ministries, and

[46] Estonian Environmental Registry. (2024). *Annual reports registry*. Estonian Ministry of the Environment. https://kotkas.envir.ee/annual_reports_registry?represented_id=

[47] EC. (2024). *EU Emissions Trading System (ETS) compliance management*. https://ec.europa.eu/clima/ets/allocationComplianceMgt.do

some preparation work is ongoing. The governmental financial support of these plans is discussed in the Estonian parliament.

VKG is a private company owned by VKG Energia North Thermal Plant and VKG Shale Oil Plant, producing a full range of chemistry. Kiviõli Keemiatööstus, Alexela Group, own Kiviõli Chemical Plant. Horizon Paper Factory produces bio emissions and is located in Kehra, about 40 km from Tallinn. UTILITAS is the largest producer of renewable energy in Estonia, supplying heat and electricity to hundreds of thousands of people. It produces mainly bio-CO_2 emissions.

Eight Estonian plants in the Baltic Scenario produced 3.9 Mt/y CO_2, including 6.8 Mt/y of bio-CO_2 (Table 8).

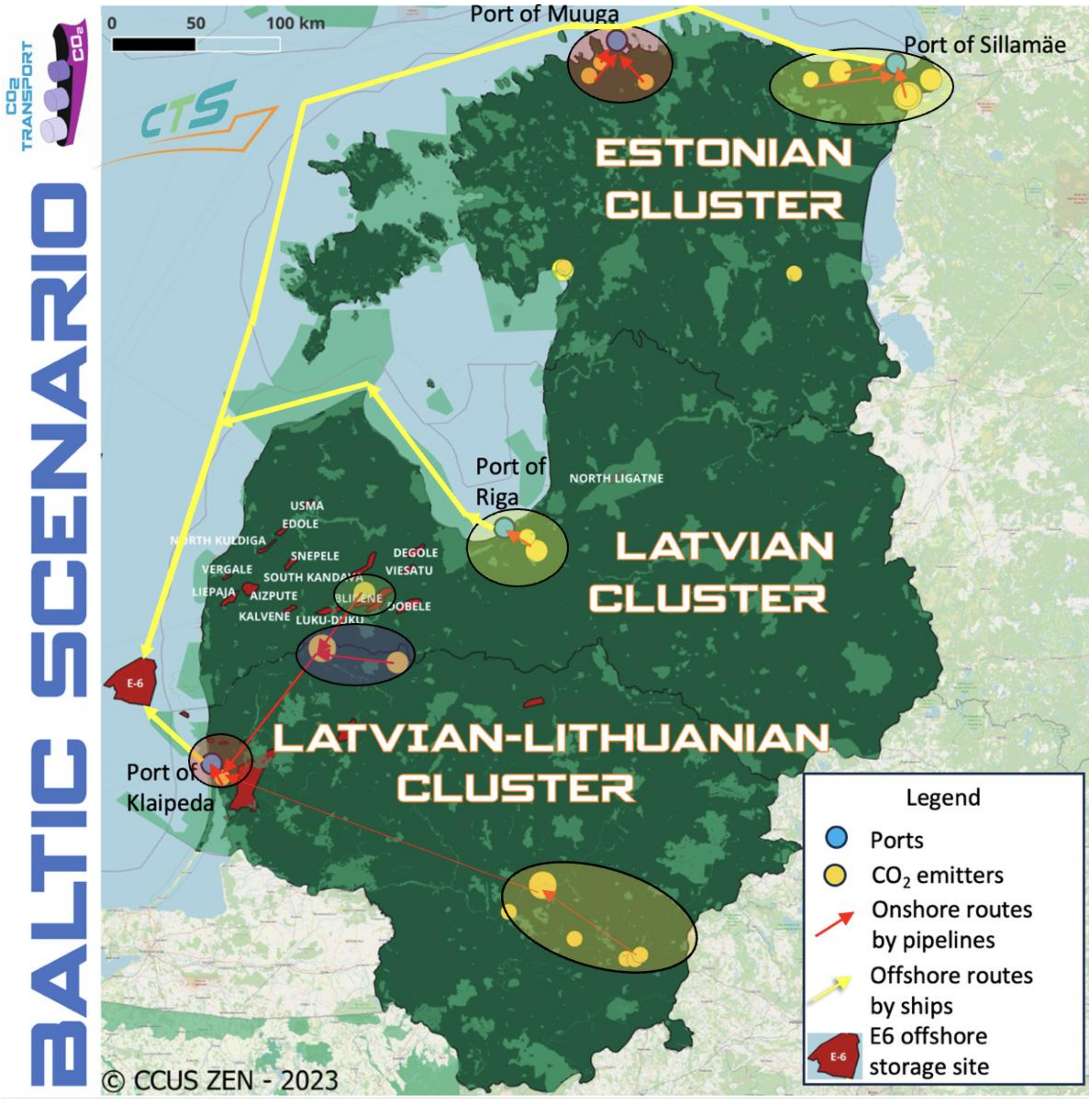

Figure 14. Baltic Cross-Border Scenario: 14 emitters in three Baltic countries (Estonia, Latvia, and Lithuania) located near ports produced 9.4 Mt of CO_2 in 2023. The green colour transparent circle shows the Ida-Viru (NE) cluster to Sillamäe Port, the red-Tallinn-Harju cluster to Muuga Port, the blue-Latvian Cluster (Riga Port) and the yellow one is Latvian - Lithuanian Cluster (Klaipeda Port). This CO_2 will be transported by pipelines to the ports and then to the E6 offshore geological structure via ships. A unique injection technology developed in the CTS project will directly inject captured CO_2 from the ships into the underground geological structure at a depth of over 850 m.

5.2.2 Latvia

The largest CO_2 emitters in Latvia included in the Baltic Scenario are the national energy Company Latvenergo and Schwenk Cement Latvia. Both companies are planning to capture CO_2. Schwenk Latvia also bought a cement plant in Lithuania, Akmenes Cement (Table 9). SCHWENK's Building Material Group's Broceni already ordered capture technology from CapsolGo® to demonstrate technology in the Baltic CCS Consortium (PCI)[48]. They will capture 1.5 Mt CO_2 from two plants and transport it by railway or trucks to Klaipeda Port for CO_2 storage in the North Sea.

Three Latvian plants in the Baltic Scenario produced 1.44 Mt/y CO_2 in 2023 (Table 9).

Table 9. Emitters from Latvia included in the Baltic Scenario[47].

Number	EU ETS ID of the plant	Plant Name	Region/City	Sector	CO_2 emissions 2023, t/y
1	KU20SG0008	Schwenk Latvia	Saldus/Broceni	Cement	744,135
2	LV-RIT-R-II-SEG-07	Latvenergo Tec-2	Riga/Salaspils	Power	546,285
3	LV-RIT-R-II-SEG-06	Latvenergo Tec-1	Riga	Power	154,079
	Total CO_2 emissions 2023				1,444,499

5.2.3 Lithuania

Orlen Oil Company and Gren (previously owned by Fortum) are international companies planning and developing CO_2 capture and CCS projects for several years. Orlen has similar activities in Poland, while Gren is mainly active in Nordic countries.

Orlen Lietuva (Table 10) is involved in the Polish Gdansk PCI projects, while Fortum participates in the EC projects funded by the Innovation Fund.

Gren is a Nordic energy company that provides clean, cost-effective, and reliable energy solutions to communities and businesses. Gren is actively expanding its operations and investing in sustainable energy projects across Northern Europe.

UAB Kauno Kogeneracinė Jėgainė is a technologically advanced cogeneration plant in Lithuania, converting non-hazardous industrial and municipal waste into electricity and heat. The plant significantly contributes to the energy needs of Kaunas, covering nearly half of the city's heat demand.

Achema is a leading producer of nitrogen fertilisers and chemical products in Lithuania and the Baltic states. Established in 1965, the company operates a large factory in Jonava, producing a wide range of products, including ammonia, nitric acid, and urea. Achema is committed to sustainable production and environmental protection.

Five Lithuanian plants in the Baltic Scenario produced about 4 Mt/y CO_2 in 2023 (Table 10).

[48] **CCUS Expo.** (2024). *Capsol demo campaigns ordered by Schwenk for two cement plants*. CCUS Expo. https://www.ccus-expo.com/industry-news/capsol-demo-campaigns-ordered-schwenk-two-cement-plants.

Table 10. Emitters from Lithuania included in the Baltic Scenario[47].

Number	EU ETS ID of the plant	Plant Name	Region/City	Sector	CO_2 emissions 2023, t/y
1	T-KL1-3-2014	Gren Klaipėda WtEP	Klaipeda	WtE	100,151
2	T-S-4-6-2015	Orlen Lietuva	Telšiai	Refineries	1,646,257
3	T-S-1-1-2014	Akmenės Cement	Akmene	Cement	783,849
4	T-K-4-24-2019	UAB Kauno WtEP	Vilnius	WtE	119,661
5	2-15	Achema	Jonavos Region	Chemical	1,363,398
	Total CO_2 emissions 2023				4,013,316

Achema is a leading producer of nitrogen fertilisers and chemical products in Lithuania and the Baltic States.

5.3 CO_2 Storage Site

E6 offshore structure in the Cambrian Deimena Formation sandstone saline aquifer is one of the most promising CO_2 storage sites in the Baltic Region. In the 50 m thick sandstones of the E6 geological structure, located 30 km from the Latvian shore, approximately 365 million tons of CO_2 can be stored at a depth of over 850 m[50,51].

Previous studies show that the most prospective structures for CO_2 geological storage (CGS) in the Baltic region (Estonia, Latvia and Lithuania) are available in Latvia, represented by several onshore and offshore anticline structures. The main target is the Baltic Basin (700 km × 500 km synclinal structure), a Late Ediacaran–Phanerozoic polygenetic sedimentary basin developed in a peri-cratonic setting in the western part of the East European Platform. It overlies the Paleoproterozoic crystalline basement of the East European Craton, specifically the West Lithuanian Granulite Domain, flanked by terranes of the Svecofennian Orogen southeast of the Baltic Sea. Basin fill consists of Ediacaran–Lower Palaeozoic, Devonian–Carboniferous and Permian–Mesozoic successions, coinciding with what is referred to as the Caledonian, Variscan and Alpine stages of the tectonic development of the basin, respectively. These are separated by regional unconformities and overlain by a thin cover of Cenozoic deposits. Several structures have been singled out in the Latvian part of the Baltic Syneclise. The Estonian–Latvian and Lithuanian monoclines are the marginal structures of the Baltic Syneclise.

The Liepaja depression (Figure 15) is a distinctly asymmetrical depression (length 200 km, width up to 70 km, trough amplitude 800 m) with a gentle northern and a steep near-fault southern edge. The Liepaja–Saldus zone of highs crosses the Baltic Syneclise, stretching from the Swedish offshore towards the northeast for about 400 km (Figure 15). The width of the zone is 25–80 km. From northeast to southwest, the basement submerges from 500 to 1900 m. The Liepaja–Saldus zone is a complex system of disjunctive-plicative dislocations, the intensity of which exceeds that in other areas of the Baltic Syneclise. The amplitude of uplift in the anticline structures reaches 600 m. The Gdansk–Kura depression (Figure 15) is only represented by its northern peripheral part. The South Latvian step, about 100 km long, is a sub-latitudinal tectonic block in southern Latvia. The amplitudes of boundary faults reach 400–500 m.

Clayey Cambrian, Ordovician, and Silurian rocks are the principal source rocks of the Baltic Syneclise. In Latvia, Cambrian, Ordovician, and Lower Silurian rocks are at the early maturation stage, the depth of the basement being 1300–2000 m. Thus, the main oil generation area is the Gdansk-Kura depression. The Liepaja depression, the Pape-Barta trough, and adjacent submerged parts of the Liepaja zone of highs may be considered the local oil kitchen. One oil field, Kuldiga, was discovered in the Middle Cambrian, and nine small accumulations in Ordovician have been found in Latvia. Some oil prospects can exist in conjunction with Silurian carbonates[49].

The E6 offshore structure was found by seismic exploration and explored in 1984 by one well, E6-1 (depth 1068 m), located 37 km from the coast of Latvia. The structure coincides with the zone of Liepaja-Saldus Uplift and was estimated as prospective for oil in the 10.5 m thick oil-bearing reservoir layer of the Saldus Formation in the Upper Ordovician Porkuni Stage[50,51].

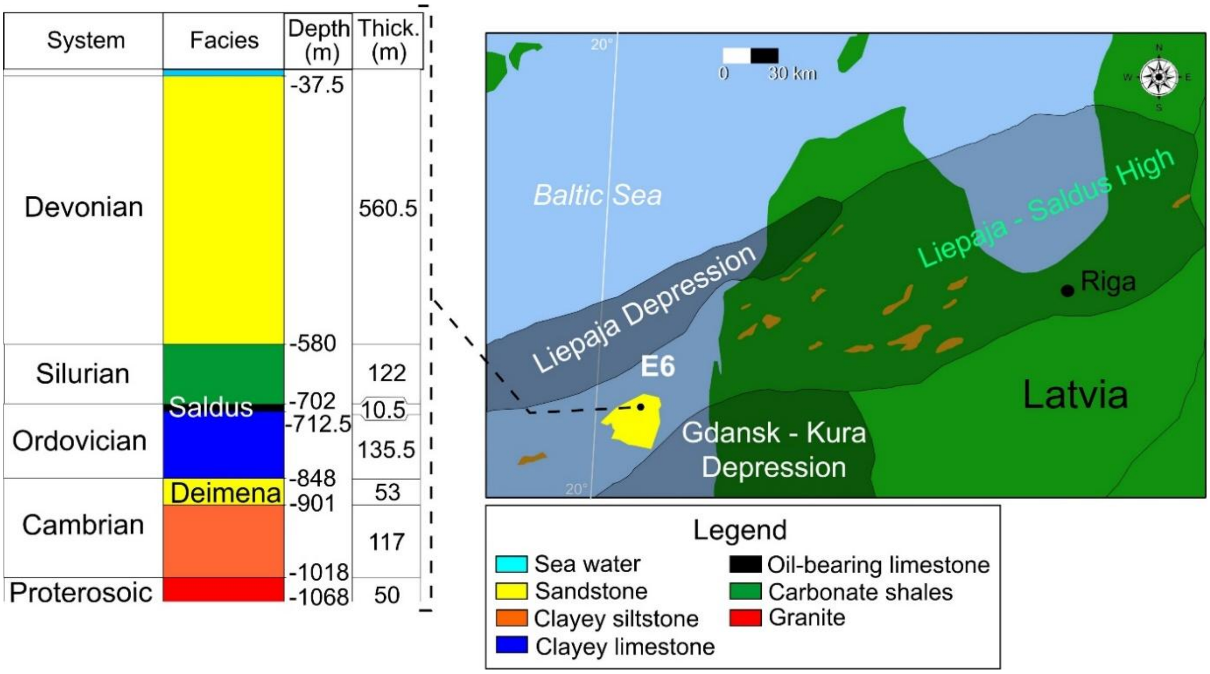

Figure 15. Locations of Latvian onshore structures and the E7 structure offshore Lithuania (brown) prospective site for CGS (CO_2 storage potential exceeding 2 Mt) in the Cambrian aquifer and the studied E6 structure offshore Latvia (yellow), with the location of the well and complete lithological cross-section. The Cambrian Deimena Formation of sandstones prospective for CGS and limestone oil reservoir of the Ordovician Saldus Formation prospective for CO_2-EOR and EOR+ of the E6 structure are shown on the lithological cross-section. Large regional structures complicating the Baltic Syneclise in the study area are displayed on the map according to[52].

The fractured-porous Ordovician oil reservoir of the Saldus Formation, related to VI class reservoirs[53], is represented mainly by oil-bearing carbonate rocks: coarse clastic limestones with oolites. At the same time, oolitic limestones and subordinate calcareous quarzitic aleurolites are also present. From

[49] Freimanis A, Margulis LS, Brangulis A, Kanev S, Pomerantseva R. Geology and hydrocarbon prospects of Latvia. OGJ 1993; 91(49):71-74.
[50] Shogenov K, Shogenova A, Vizika-Kavvadias O. Petrophysical properties and capacity of prospective structures for geological storage of CO_2 onshore and offshore Baltic. Elsevier, Energy Procedia 2013; 37:5036-5045. DOI:10.1016/j.egypro.2013.06.417.
[51] 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.
[52] Poprawa P, Šliaupa S, Stephenson R, Lazauskiene J. Late Vendian-Early Palaeozoic tectonic evolution of the Baltic basin: regional tectonic implications from subsidence analysis. Tectonophysics 1999; 314:218-239.
[53] Багринцева КИ. Карботнатные породы-коллекторы нефти и газа. Москва: Недра; 1977.

the palaeographical point of view, it means the shallow sediments of the Jelgava Depression and the SE slope of the Central Baltic Elevation[54]. The rocks have good reservoir properties: the open porosity varies from 10 to 24% (average 18%), and gas permeability reaches 39 mD (average 6 mD) in well E6-1[54,55].

The fault system within the structure has led to the migration of hydrocarbons from the Cambrian reservoir to the upper Ordovician reservoir[56]. The owner of the license for oil exploitation in the E6 structure is the Danish oil company Odin Energi A/S. The oil reserves of the E6 structure, estimated by the license owner, are 362 MMBO (million barrels of oil), equivalent to the maximum closure of 585 km^2. Oil flow was very low during exploration: 2.7 m^3/day from 700 m deep Saldus reservoir due to low pressure within the reservoir and relatively heavy oil. No water flow from Porkuni beds was determined. Therefore, hydro-chemical data, as exploration criteria, are not available[54].

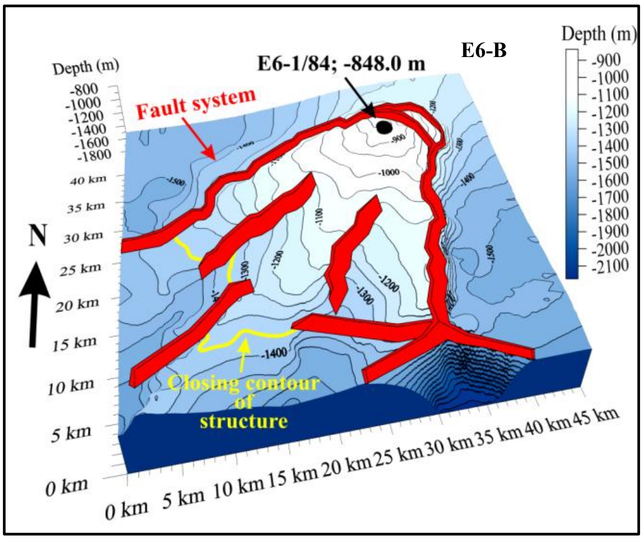

Figure 16. A static model of the E6 storage site offshore Latvia[50,51]

Oil shows were also found in the sandstones of the Cambrian Series 3 Deimena Formation and the Devonian rocks of the offshore E6 structure. Prospective for the CGS reservoir of the Cambrian Series 3 Deimena Formation (848–901 m depth at the well E6-1/84) in the E6 structure was assessed as the largest storage site among all the studied in the Baltic Region structures. Conservative and optimistic CO_2 storage capacity of the Deimena Formation sandstone reservoir in part A of the E-6 structure was estimated at 146–365 million tonnes (Mt), respectively (Table *11*). The CO_2 storage capacity of the total Cambrian reservoir (parts A and B) is 152–377 Mt[51]. The Deimena Formation rocks are composed of dark- and light-grey, fine-grained, loosely and medium-cemented quartz oil-impregnated sandstones. The rocks were deposited in a shallow regressing marine basin subjected to tides and storms and are dominated by quartz sandstones with subordinate claystone layers (mud shelf). The poorly sorted sandstones of various grain sizes, containing gravel fraction, were deposited at the end of Deimena time. The major Deimena reservoir lies regressively on the Kybartai Formation. The regression was associated with the sandier composition of deposits. Numerous faults dissect the Cambrian reservoir body. They form essential pathways for fluid migration, while high-amplitude faults block fluid

[54] Zdanavičiute O, Sakalauskas K. (eds). Petroleum Geology of Lithuania and southeastern Baltic. Vilnius. (2001), 204 pp.
[55] Shogenov K, Gei D, Forlin E, Shogenova A. Petrophysical and numerical seismic modelling of CO_2 geological storage in the E6 structure, Baltic Sea, Offshore Latvia. Petroleum Geoscience. (2016), 22:153–164. DOI:10.1144/petgeo2015-017
[56] Šliaupiene R, Šliaupa S. Risk Factors of CO_2 Geological Storage in the Baltic Sedimentary Basins. Geologija. (2012), 54(3):100-123.

migration in the uplifted structures. The structure is an anticline fold bounded on three sides by faults. The E6 structure comprises two different compartments divided by inner fault[55] (Figure 16). The total area of the structure is 600 km^2, considering the closing contour of the reservoir top, which is located at a depth of 1350 m below sea level (BSL). The average thickness of the reservoir unit is 53 m.

Cambrian Wuliuan (earlier Series 3 and before it, Middle Cambrian) saline aquifer (depth 700–1700 m) located in the central-western part of the Baltic Basin is best for CO_2 storage in the Baltic Region. It comprises 25–80 m thick Deimena Formation sandstone unconformably covered by up to 46 m thick shales and clayey carbonates of primary cap rocks of the Lower Ordovician Zebre Formation. Shale rocks are dark, thin-layered (0.5–2 mm) and highly fissile. A 0.5 m layer of greenish-grey glauconite-bearing sandy marlstones with minor limestone lenses is observed at the base of the onshore Zebre Formation. The reservoir rocks are also covered by 130–230 m thick Ordovician (146 m thick in the well E6-1) and 100–225 m thick Silurian (122 m thick in the well E6-1) impermeable clayey carbonate secondary cap rocks, consisting mainly of shales, marlstones and clayey limestones [57] (Figure 15).

Table 11. Parameters of Deimena Formation sandstone reservoir in CO_2 storage site E6-A selected for the Baltic scenario.

Parameters	**E6-A**
Depth of reservoir top (min–max), m	848–901
Reservoir thickness, m	53
Trap area, km^2	553
CO_2 density, kg/m^3	658
Net to gross ratio, %	90
Salinity, g/l	99
Permeability (min–max/avg), mD ($10^{-16}m^2$)	10–440 (160)
T, °C	36
Storage efficiency factor Optimistic/Conservative, %	10/4
Porosity (min–max/avg), %	14–33/21
Optimistic CO_2 storage capacity (min–max/avg), Mt	243–582/365
Conservative CO_2 storage capacity (min–max/avg), Mt	97–233/146

The porosity of the Cambrian Series 3 Deimena Formation reservoir sandstones is in the range of 14–33% (21% mean), and permeability is in the range of 10–440 mD (160 mD mean) (Table 11). The average porosity and permeability of the Ordovician cap rock are 3% and <0.01 mD, respectively. The Cambrian aquifer includes potable water in the northern shallow part of the Baltic Basin, mineral water

[57] Shogenova A, Shogenov K, Vaher R, Ivask J, Sliaupa S, Vangkilde-Pedersen T, Uibu M, Kuusik R. CO_2 geological storage capacity analysis in Estonia and neighboring regions. Elsevier, Energy Procedia. (2011), 4, 2785-2792.

(salinity 10 g/l) in southern Estonia and saline water in the Deimena Formation at more than 800 m depths, with salinity up to 120 g/l in the central and 150–180 g/l in the southern and western parts of the basin, where the fluid temperature reaches 88°C[54]. The last mentioned geochemical and pressure-temperature conditions of formation fluids allow the use of the Deimena Formation reservoir for CGS at depths of 800–2500 m, where CO_2 can be stored in a supercritical state (pressure >73 ATM and temperature >31°C)[58].

5.4 CO_2 Transport

In the Baltic Scenario, captured CO_2 emissions from 16 emitters from 4 clusters will be transported by pipelines to 4 ports in Estonia, Latvia and Lithuania and by ships from the ports to the E6 storage site in Latvia (

Table *12*).

Estonia, Latvia and Lithuania are the Baltic Sea countries. Therefore, they have many ports, some close to the most significant clusters of CO_2 emissions in the Baltic States. While selecting ports for the CCS scenario, we decided to limit the number of ports to a maximum of 1–2 per country and to apply two pre-conditions: 1) their close location to the emitters cluster, or 2) the port is already included and under development in the European PCI.

Tallinn, the capital of Estonia, has a population of about 0.5 million and hosts a major port in Tallinn. **Muuga Harbour**, part of Tallinn Port, is Estonia's largest and deepest port, handling 50% of the country's total cargo volume[59]. **Sillamäe Port**, strategically located near the EU-Russia border, was chosen for its proximity to major CO_2 emitters in northeastern Estonia[60]. The largest Estonian emission clusters (North-Eastern and Tallinn clusters) could be transported to these ports and then to the E6 offshore storage site in Latvia.

In Latvia, the largest CO_2 emitters are located in Riga, the capital of Latvia. **Riga port** is on the eastern Baltic coast at the mouth of the Daugava River, around 15 kilometres inland from the Gulf of Riga. The largest port of Latvia is also the second biggest in the Baltic region. The port is an integral part of the capital city, covering 11% of its territory. Riga port covers 6348 hectares and contains 18 km of berthing line divided among 36 multifunctional cargo terminals[61]. Riga port was selected to handle CO_2 emissions from Latvenergo power plants in the Riga region.

In Lithuania**, Klaipeda Port**, included in the CCS Baltic Project of Common Interest (PCI) coordinated by Klaipeda Nafta, is planned to host a CO_2 loading terminal. Klaipeda Port, one of the few ice-free ports in northern Europe, is a central hub for freight and cruise ships capable of accommodating large vessels.[62] The port is well-connected by rail and road to Kaunas and Vilnius, facilitating the transport of CO_2 emissions from Latvian and Lithuanian plants to Klaipeda Port.

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[58] Shogenov, K., Shogenova, A., Gei, D. & Forlin, E. 2017. Synergy of CO2 storage and oil recovery in different geological formations: case study in the Baltic Sea. Elsevier. Energy Procedia, 114, 7047-7054. https://doi.org/10.1016/j.egypro.2017.03.1846
[59] Tallinna Sadam. *Muuga harbour*. https://www.ts.ee/en/muuga-harbour/
[60] Silport. *Silport port services*. https://www.silport.ee/eng
[61] https://rop.lv/en/port-location
[62] Port of Klaipeda. *Port - Uostai-WP*. https://portofklaipeda.lt/en/port/

Table 12. Transport distance by pipelines from CO_2 emitters included in clusters to ports and from ports to the E6 storage site in Latvia by ships in the Baltic scenario.

Country and Cluster	N	Plant Name	Region/Town	Sector	CO_2 produced in 2023, t/yr	Pipeline distance to Port (km)	Ship Distance from port to E6 site, km
ESTONIA – **Ida-Viru (NE) cluster to Sillamäe port**	1	Auvere PP	Ida-Viru /Auvere	Power	937,197	**25.2** (From SOP to the port, **1.3 km** between Auvere plants along the road, **26.5 km in total**)	751
	2	Auvere SOP	Ida-Viru /Auvere	Shale Oil Plant	975,506		
	3	VKG SOP	Ida-Viru /Kohtla-Järve	Shale Oil Plant	721,077	**19.8** (from SOP to the port, **1 km** between VKG plants using railway, **20.8 in total**)	
	4	VKG Energia North TP	Ida-Viru /Kohtla-Järve	Power	619,974		
	5	Kiviõli Chemical Plant	Ida-Viru/ Kiviõli	Shale Oil Plant	231,536	**37.3** (from the plant to VKG hub, from VKG **19.8 km**. **In total 57.1 km**)	
		Total			**3,485,290**	**104.4**	
Tallinn-Harju cluster to Muuga Port	6	Horizon Paper Factory	Harju/Kehra	Paper	125,341	**32.7**	575
	7	Utilitas Tallinn PP	Harju/Tallinn	Power	156,219	**3.7** (from the plant to Iru WtE)	
	8	Iru WtE	Mardu/Iru	WtE	151,776	**9.6** (from the plant port)	
		Total			**433,336**	**46**	
	Total for Estonian clusters				**3,918,626**	**150.4**	
Latvian Cluster (Riga port)	1	Latvenergo Tec-2	Salaspils	Power	546,285	**15.1** (from Tec-2 to Tec-1)	402
	2	Latvenergo Tec-1	Riga	Power	154,079	**7.5** (from Tec-1 to port)	
	Total for Latvian Cluster				**700,364**	**22.6**	
Latvian - Lithuanian Cluster (Klaipeda Port) – West Lithu-anian sub-cluster	1	Gren Klaipeda WtE	Klaipeda	WtE	100,151	**11.2** (from Gren WtE to Port)	90.5
North Lithuanian sub-cluster	2	Orlen Lietuva (LT)	Telšiai	Refinieries	1,646,257	**116** (Orlen LT to Gren Klaipeda WtE)	
	3	Akmenės Cement	Akmene	Cement	783,849	**51.23** (Akmenes Cementas to Orlen LT)	

Country and Cluster		N	Plant Name	Region/Town	Sector	CO_2 produced in 2023, t/yr	Pipeline distance to Port (km)	Ship Distance from port to E6 site, km
	Latvian sub-cluster	4	Schwenk Latvia	Saldus/Broceni	Cement	744,135	**73.44** (from Schwenk to Orlen)	
	Kaunas sub-cluster	5	AB Achema	Jonavos Region	Ammonia	1,363,398	**230.5** (from Achema to Klaipeda Port)	
		6	UAB Kauno WtEP	Vilnius	WtE	119,661	**95** (from UAB Kauno to Achema)	
		Total for Latvian - Lithuanian Cluster				**4,757,451**	**577.37**	
Total for Baltic Scenario						**9,376,441**	**750.37**	**1818.5**

5.5 CO_2 Use

In the Baltic Sea scenario, it is planned to use at least 10% of the captured CO_2 for CCU to produce CO_2-based products, which is about 0.9 Mt/y (Table 13). After 2040, only bio-CO_2 could be used for CO_2-based products, according to the EU Industrial Act.

In the Baltic Scenario, the planned utilisation of 0.9 Mt/y CO_2 corresponds to 0.9 Mt/y bio-CO_2 produced and reported by Estonian and Lithuanian plants included in the scenario. In Estonia, this bio-CO_2 is produced by Auvere PP using bio-waste and oil-shale for co-generation of energy, by UTILITAS using biomass and waste heat for heat and electricity production and by paper and WtE plants. The CO_2 use mineral carbonation case in Estonia is provided in chapter 5.5.1.

Table 13. CO_2 emissions produced, captured, used and transported in the Baltic Sea Scenario.

Cluster to Port	Number of plants	CO_2 produced 2023, Mt/y	CO_2 captured Mt/y	CO_2 used Mt/y	CO_2 transported Mt/y	Pipelines distance to port, km	Ship distance from port to storage site, km
Ida-Viru cluster to Sillamäe Port, Estonia	5	3.5	3.3	0.33	2.99	**104.4**	751
Tallinn-Harju cluster to Muuga Port, Estonia	3	0.43	0.41	0.04	0.37	**46**	575
Latvian Cluster to Riga port	2	0.7	0.67	0.07	0.6	**22.6**	402
Latvian-Lithuanian Cluster to Klaipeda Port in Lithuania	6	4.8	4.56	0.46	4.1	**577.37**	90.5
Total	**16**	**9.43**	**8.94**	**0.9**	**8.06**	**727.77**	**1818.5**

In Lithuania, two WtE plants mainly producing bio-CO_2 are included in the Baltic scenario. In the future, replacing natural gas used by Latvenergo plants and any other Baltic plants with biogas will be possible. This option will provide even more possibilities for CCU to get to negative emissions by storing bio-CO_2.

It is expected that part of the captured CO_2 will also be used in the Baltic States to produce renewable green fuels and chemical products. The percentage of CO_2 used could be increased by natural gas being replaced by biogas, and more WtE plants will apply CO_2 capture, resulting in a higher share of bio-CO_2 captured in CCUS projects.

5.5.1 CO_2 Use Case in Estonia

Estonia's commitment to reducing CO_2 emissions has led to innovative projects in CCUS. A notable example is the collaboration between Ragn-Sells and Tarkett, focusing on transforming oil shale ash into valuable products[63].

Ragn-Sells' Oil Shale Ash Valorisation Project

Over the past decades, Estonia has accumulated over 600 million tons of oil shale ash from energy production[63]. Ragn-Sells has developed a patented process to extract precipitated calcium carbonate (PCC) from this ash, utilising CO_2 in the process[64]. This approach not only mitigates waste but also produces a carbon-negative material[64].

Technical Parameters

The planned facility aims to process approximately 1.3 Mt of oil shale ash annually, capturing around 250 kt of CO_2 to produce nearly 500 kt of ultra-pure PCC yearly[65] (Table 14). The process involves the following key parameters:

Table 14. Technical parameters[65].

Parameter	**Value**
Annual ash processing, Mt/y	1.3
Annual CO_2 utilization, Mt/y	0.25
Annual PCC production, Mt/y	0.5
CO_2 capture per ton of PCC, t	0.5
CO_2 to ash to PCC ratio	1:5.2:2

Note: The CO_2-to-ash-to-PCC ratio indicates that for every ton of CO_2 captured, 5.2 tons of ash are processed to produce 2 tons of PCC.

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[63] Tarkett. (n.d.). *Tarkett & Ragn-Sells collaboration*. Retrieved from https://professionals.tarkett.com
[64] Ragn-Sells. (2023). *From ash piles to a carbon-negative raw material*. Retrieved from https://newsroom.ragnsells.com
[65] Ragn-Sells. (2024). *Location chosen for oil shale ash valorization facility*. Retrieved from https://www.ragnsells.com

Economic Considerations

The project is expected to bring approximately €250 million in investments to the region, creating up to 100 direct jobs and 400 indirect jobs[65]. While specific economic figures are proprietary, the project's scale suggests significant capital investment, with anticipated positive returns from the sale of PCC and environmental benefits[65] (Table 14).

Table 15. Economic parameters[65].

Economic Factor	Value
Estimated investment	250 M€
Direct jobs created	100
Indirect jobs created	400

CO_2 Source and Future Considerations

Currently, the project utilises CO_2 emissions from oil shale combustion[63]. However, with regulatory changes, including Estonia's Industrial Act and upcoming EU regulations, there will be a shift from fossil-based CO_2 to biogenic CO_2 sources by 2040[66] (Table 15).

Table 16. CO_2 Source and Future Considerations[65].

CO_2 Source	Current	Future (by 2040)
Primary source	Oil shale combustion emissions	Biogenic CO_2
Potential biogenic sources	Wood and forestry industry	Waste-to-energy plants, pulp and paper industry

The Circular Bioeconomy Roadmap for Estonia emphasises the increased utilisation of bio-resources, suggesting that bio-waste processing will play a significant role in the country's energy and material production strategies post-2040[66].

The Ragn-Sells project exemplifies how Estonia is turning environmental challenges into opportunities through CCUS technologies. By repurposing industrial waste and aligning with future regulatory frameworks, Estonia is paving the way for sustainable industrial practices.

5.6 Summary

The Baltic scenario includes CO_2 emissions from Estonia, Latvia, and Lithuania, with pipeline and ship transport to CO_2 storage planned in the E6 structure offshore Latvia (Figure 14). CO_2 will be transported by pipelines to ports and by ships from ports.

In total, about 8.1 Mt/y captured CO_2 produced by 16 plants from 4 clusters located in three countries will be transported by ships from four ports to the E6 storage site with a total shipping distance of

[66] Estonian Ministry of Agriculture. (2023). *Circular Bioeconomy Roadmap for Estonia*. Retrieved from https://agri.ee

about 1820 km (Table 13). The pipeline distance to ports will be 10 km (from Iru WtE in Tallinn) to 230 km (from Achema in Kaunas).

From Estonia, about 3 Mt/y CO_2 from 3.5 Mt/y CO_2 produced by five plants in the Ida-Viru cluster will be transported by 82 km pipelines to NE Sillamäe Port and then by ship to E6 structure in Latvia (751 km).

Additionally, 0.41 Mt/y CO_2 from 0.43 Mt/y CO_2 produced by three Estonian plants in the Tallinn-Harju cluster will be transported to Muuga Port (part of Tallinn Port) by pipelines (46 km) and then by ship to E6 structure in Latvia (575 km).

From the Latvian cluster, 0.67 Mt/y CO_2 from 0.7 Mt/y produced by two Latvenergo Natural Gas power plants will be transported to Riga by pipelines (22.6 km) and then by ships to the E6 structure offshore (402 km).

Six plants from the Latvian-Lithuanian cluster producing 4.8 Mt/y CO_2 will transport 4.1 Mt/y CO_2 by pipelines to Klaipeda (577.4 km) and then by ships to the E6 structure offshore (90.5 km).

The total shipping distance from the three ports is about 1820 km. The total CO_2 emissions produced is 9.43 Mt/y. The total captured CO_2 emissions (95%) is about 8.49 Mt. Considering 10% of CO_2 used (0.9 Mt/y), about 8.1 Mt CO_2 will be transported from four ports in three countries and injected into E6-A part of the E6 structure in Latvia.

In the Baltic Sea scenario, it is planned to use at least 10% of the captured CO_2 for CCU to produce CO_2-based products. A patented process developed in Estonia by Ragn-Sells to make precipitated calcium carbonate (PCC) from oil shale ash and captured CO_2 will support the utilisation of about 0.25 Mt/y CO_2 along with 1.3 Mt of the burnt oil shale (oil shale ash) and produce 0.5 Mt/y of PCC. Another part of the planned utilisation of CO_2 (0.65 Mt) is expected to produce renewable e-fuels and chemical products in Estonia and Lithuania. After 2040, only bio-CO_2 could be used for the last-mentioned products, considering their short life cycle. In the Baltic Scenario, the planned utilisation of 0.9 Mt/y CO_2 corresponds to 0.9 Mt/y bio-CO_2 produced and reported by Estonian and Lithuanian plants included in the scenario.

6. Black Sea Scenario

The Black Sea scenario comprises Ukrainian and Romanian scenarios involving the possible implementation of CCS and direct ship injection technology in the northern part of the western Black Sea basin. The scenarios at this stage are designed per country. After a preliminary techno-economic assessment of individual scenarios, a combined Baltic scenario will be developed and evaluated later in the project.

6.1 Romania

6.1.1 Introduction

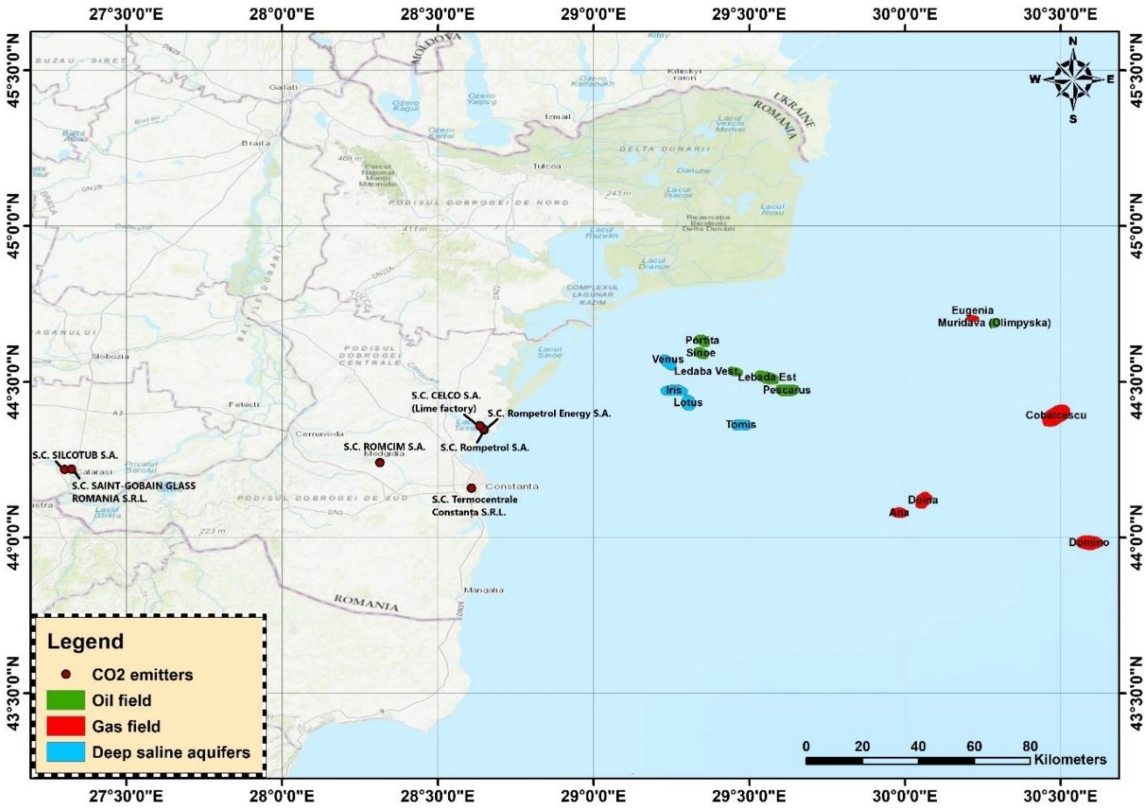


Figure 17. Map of emitters and storage sites for the Romanian scenario.

Romanian scenario (Figure *17*) includes basically the capture of CO_2 from Călărași and Constanța area, transport of CO_2 via the Danube and Danube - Black Sea Channel, intermittent storage in Călărași, Medgidia and Midia ports, maritime transport from Mida to offshore storage sites in deep saline aquifers and depleted or soon to be depleted hydrocarbon fields. Three options for transporting CO_2 from Midia to the offshore storage sites are considered: offshore pipeline, conventional ship transport and direct ship injection. For the scenarios resulting from these options in transport, a techno-economic analysis will be made together with a comparison that will conclude on the feasibility of using the direct ship injection technology in the Romanian scenario.

Regarding GHG emissions reduction at the country level, Romania submitted its final National Energy and Climate Plan (NECP) for 2030 in October 2024, setting an 85% reduction target of GHG emissions compared to the 1989 reference year. CCS is touched briefly in the report, and no concrete targets for capture are described. Although no CCS project exists in Romania today, the regulatory framework exists. The CCS Directive was transposed through Law 114/2013 and amended in December 2024. At the present time CO_2 storage offshore Romania is permitted according to national CCS law and its recent amendments.

6.1.2 CO_2 Emissions

The Romanian scenario was initially derived from the scenario built for implementing CCUS in the Galați region within the STRATEGY CCUS project. Due to the region's industrial decline and a significant CO_2 emitter from Tulcea closing, new emitters with active businesses have been considered CO_2 sources in the CTS scenario presented here. The main scenario involves the capture of CO_2 from Călărași, Medgidia and Constanța areas and storage in the offshore structures (depleted hydrocarbon fields and deep saline aquifers) in the Black Sea.

For the Romanian scenario, CO_2 emitters from Călărași and Constanța (including Medgidia) area are considered.

Călărași is a county in south-eastern Romania, in the region of Muntenia, located on the Danube River close to the Bulgarian border. It covers an area of 5088 km^2, representing 2.1% of Romanian territory[67]. Călărași had a population of 283458 inhabitants in 2021[68]. The most important industries (Table 17) are metallurgical, food and beverage, nonferrous metallurgy, chemical, and glass and clothes manufacturing[69].

Table 17. Greenhouse gas emissions by industry and pollutant type from stationary sources in Călărași County (calculated from National Environmental Protection Agency data)[70].

Industry type	Year	CO_2 eq., t/y
Glass manufacturing	2023	100 946
Paper and cardboard manufacturing	2023	10 203
Steel and ferrous metals production	2023	64 747
Vegetable oil production	2023	8 094
Total		183 990

From the emitters listed in Călărași, only two were selected for the CTS Romanian scenario: a pig iron and steel producer and a glass manufacturing facility (Table *18*18). These two accounted for 149,140 t CO_2 eq. in 2023[70].

Table 18. CO_2 emitters data for Călărași cluster.

ID EU-ETS	Company name	Facility name	Industrial sector	Verified CO_2 emissions 2021, t/y	Verified CO_2 emissions 2022, t/y	Verified CO_2 emissions 2023, t/y
48	S.C. SILCOTUB S.A.	S.C. SILCOTUB S.A. Punct de lucru Călărași	Production of pig iron and steel	48,803	46,633	48,803

[67] https://calarasi.insse.ro/wp-content/uploads/2018/04/Geografia_judetului_Calarasi.pdf
[68] https://www.recensamantromania.ro/wp-content/uploads/2023/05/Tabel-1.03_1.3.1-si-1.03.2.xls
[69] https://www.adrmuntenia.ro/judetul-calarasi/static/1445
[70] https://www.anpm.ro/documents/12220/37839994/Emisii+GES+verificate+2021-2030+FINAL_16.04.24.xlsx/107587b1-2cbc-4c9f-90e7-c7bfedba4c1c

120	S.C. SAINT-GOBAIN GLASS ROMÂNIA S.R.L.	S.C. SAINT - GOBAIN GLASS ROMÂNIA S.R.L.	Glass manufacturing	110,775	110,180	100,946
Total				159,578	156,813	149,749

Constanța is a county in the region of Dobrogea, located between the Danube and the Black Sea, covering an area of 7071 km^2, representing 2.97% of Romanian territory (8th largest county)[71]. Constanța had a population of 748,503 inhabitants on the 1st of January 2024[72]. It is an important transportation hub, hosting an international airport and several ports on the Danube, Black Sea and the Danube-Black Sea Canal. Its industries are mainly oil and gas, electricity generation, agriculture, cement, transportation and beach tourism[73, 74].
From the Constanța area, five emitters were selected for CTS: a cement plant from Medgidia, a heat and energy plant in Constanța, an energy plant and a refinery in Midia and a lime factory (Table 19, Table *20*20). These five emitters accounted for 2,032,535 t CO_2 eq. in 2023.

Table 19. Greenhouse gas emissions by industry and pollutant type from stationary sources in Constanța County (calculated from National Environmental Protection Agency data)[75].

Industry type	**Year**	**CO_2 eq., t/y**
Oil and gas extraction	2023	29,167
Oil and gas refining	2023	835,562
Steam power plants and other burner installations over 50 MW	2023	261,668
Nuclear energy	2023	972
Production of clinker	2023	853,512
Production of lime	2023	81,793
Landfills	2016	8085
Intensive farming of domestic fowl and pigs	2016	8232
Total CO_2 equivalent (using 21 as a GWP factor for methane)		2,078,844

71 https://www.cjc.ro/sectiune.php?s=55
72 https://constanta.insse.ro/
73 https://www.zf.ro/eveniment/cum-arata-economia-din-constanta-judetul-de-la-marea-neagra-care-a-devenit-poarta-spre-noua-sonda-de-aur-negru-si-gaze-a-romaniei-13013528
74 https://ziarulamprenta.ro/stirile-zilei/vezi-aici-care-sunt-primele-10-firme-din-judetul-constanta-dupa-cifra-de-afaceri-din-2023-si-cine-sunt-actionarii-acestora/343539/
75 http://prtr.anpm.ro/ReportsEmisiiSUM.aspx

Table 20. Emitter data for Constanța cluster.

ID EU-ETS	Company name	Facility name	Industrial sector	Verified CO_2 emissions 2021, t/y	Verified CO_2 emissions 2022, t/y	Verified CO_2 emissions 2023, t/y
29	ROMCIM S.A.	ROMCIM S.A. - Medgidia	Cement production	888,902	941,198	853,512
32	S.C. CELCO S.A.	S.C. CELCO S.A.	Lime production	106,793	84,904	81,793
41	S.C. Termocentrale Constanta S.R.L.	S.C. Termocentrale Constanta S.R.L. (former CTE Palas)	Heat and energy production	147,011	120,091	110,847
89	S.C. Rompetrol Rafinare S.A.	S.C. Rompetrol Rafinare S.A. – Petromidia	Refinery	702,940	881,633	835,562
RO-64-2021	Rompetrol Energy S.A.	Rompetrol Energy S.A. (former Termoelectric facility Midia S.A.)	Energy production	125,407	143,718	150,821
Total				1,971,053	2,171,544	2,032,535

6.1.3 CO_2 Storage Sites

For the storage of CO_2 captured from Călărași and Constanța areas, four deep saline aquifers (Venus, Iris, Tomis, Lotus) and three hydrocarbon fields (Lebăda Est, Lebăda Vest and Sinoe) from Histria Depression, Black Sea, are feasible options. All the potential storage sites are shallow water, most of which have deep reservoirs (1800 to 2700 m), except Venus, which has a shallower reservoir at 1000 m depth.

The potential deep saline aquifers were selected from the non-productive structures during the 1980s exploration campaign in the Black Sea, a Romanian exclusive economic zone.

Venus' structure (Figure *18*18) presents a good storage reservoir in Eocene carbonates, with the top at 1000 m depth and the marls' primary seal at the top of the Eocene formation.

The Iris structure, bordered by Venus Lotus and Tomis North faults (Figure *19*19), has two potential storage reservoirs in the Albian and Eocene. The Albian_reservoir seems to be the best reservoir for CO_2 storage. It is represented by quarzitic sandstones with calcareous cement, with a porosity of up to 30% and a permeability of 200 mD[76]. The Senonian marly formations represent the seal of the Albian reservoir. The Eocene reservoir, consisting of fine, compact limestones with a thickness of about 700

[76] Ionescu, G, Sisman, M, Cataraiani, R, 2002. Source and Reservoir Rocks and Trapping Mechanisms on the Romanian Black Sea Shelf In: Dinu, C. and Mocanu, V. (Editors). Geology and Tectonics of the Romanian Black Sea Shelf and its Hydrocarbon Potential, B.G.F. Special Volume no. 2, pp. 67-85.

m (the entire sequence being characterized by a remarkable homogeneity), is protected by a seal represented by Oligocene clays. For capacity calculation, only the Albian reservoir has been considered.

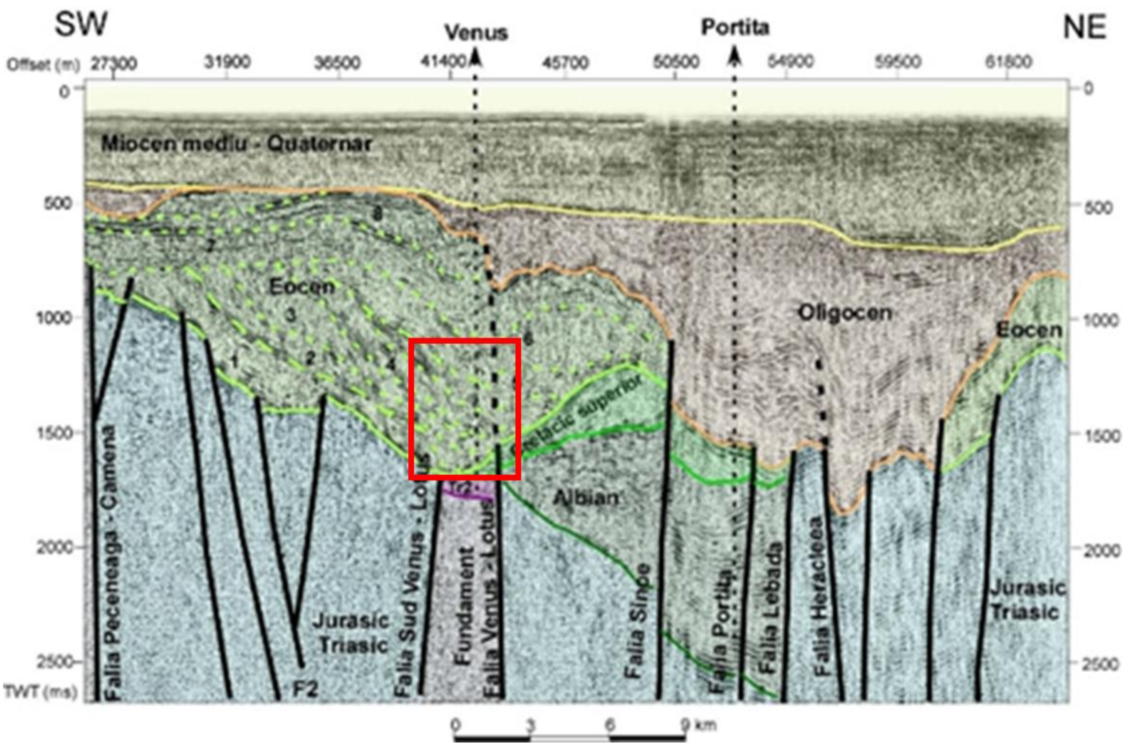


Figure 18. Venus potential deep saline aquifer (modified after Tambrea, 2007[77]).

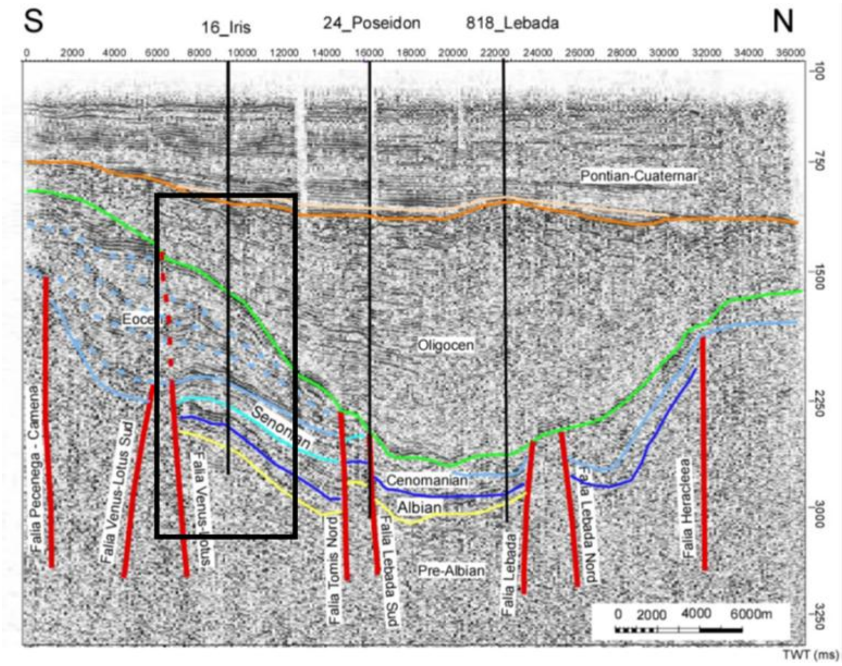


Figure 19. Iris potential storage complex (modified after Tambrea, 2007[77]).

[77] Ţambrea, D. 2007. "Subsidence analysis and tectonic-thermal evolution of the Istria Depression (Black Sea). Implications for hydrocarbon generation. " (In Romanian). PhD thesis. University of Bucharest, Faculty of Geology and Geophysics.

The Lotus structure is an anticline bounded by Venus-Lotus South and Venus-Lotus faults (Figure *20*20). The most suitable storage reservoir is the Albian, considered solely for capacity estimation, represented by calcareous sandstones (with a porosity of up to 30% and a permeability of up to 200 mD) with thin intercalations of silty clays, protected by a layer of compact blackish clays. The Eocene, the second potential storage reservoir, is very homogeneous, with an alternation of compact grey marls and fine limestones. Oligocene compact grey clays represent the seal.

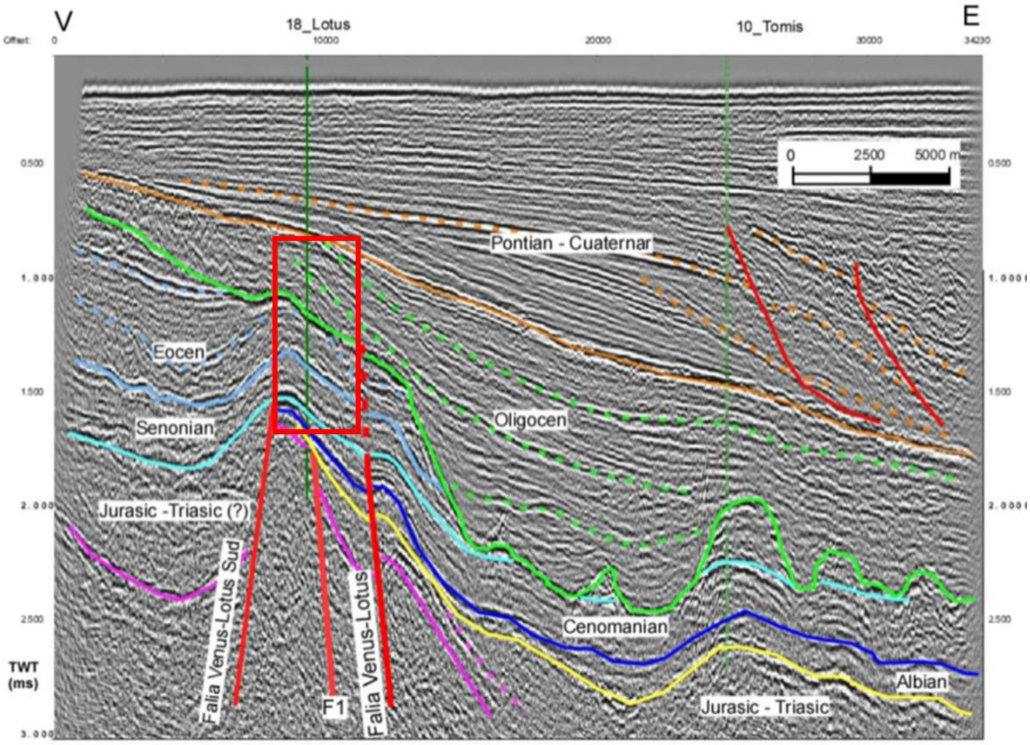


Figure 20. Potential storage complex for Lotus structure (modified after Tambrea, 2007[77])

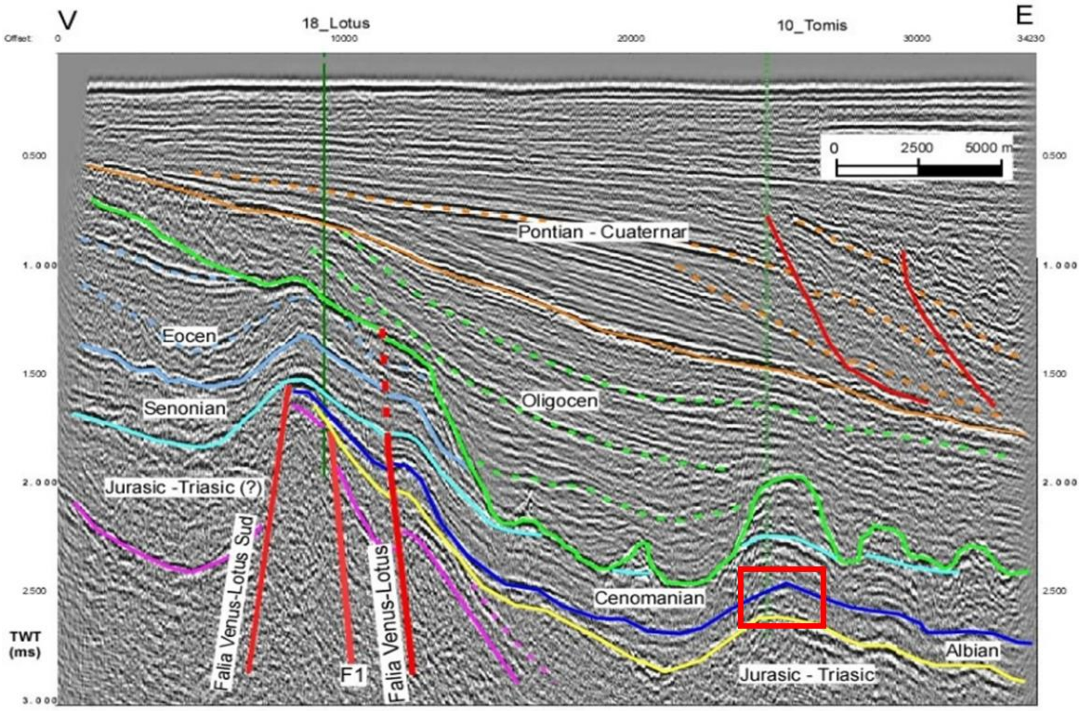


Figure 21. Potential storage complex on Tomis structure (modified after Tambrea et al., 2007[77])

Tomi's structure (Figure 2121) has a potential good storage reservoir in the Albian formation, which can reach up to 300 m in thickness in this area. The potential reservoir has been encountered at 2700–2844 m depth on 10 Tomis well77, comprised of grey sandstones with calcareous cement, with a porosity of up to 30% and a permeability of 200 mD. A thin layer of compact blackish Cenomanian marl represents the seal.

The calculation of storage capacity for the deep saline aquifers has been made according to the methodology used in EUGeoCapacity[78] after the formula:

$$M_{CO2} = A \times h \times NG \times \phi \times \rho_{CO2} \times S_{eff}$$

Where:

M_{CO2} is the storage capacity; A is the area of the aquifer; h is the average thickness of the reservoir; *NG* is an average net to gross ratio of the aquifer in the trap, where net is the thickness of the permeable reservoir layers, and gross is the total thickness of the reservoir; ϕ is average reservoir porosity; ρ_{CO2} the density of CO_2 at reservoir conditions and S_{eff} is the storage efficiency factor.

The parameters used for storage capacity calculations for the deep saline aquifers are presented in Table 2121. This is a conservative capacity estimation, choosing an average porosity of 20% for all structures, an NG ratio of 0.5 and a storage efficiency of 20%.

From the potential storage sites in deep saline aquifers, Tomis could be the more feasible option, considering it has a larger storage capacity, able to store more than 70% of the CO_2 captured under the scenario.

Table 21. Estimation of storage capacity for the deep saline aquifers of the Romanian scenario.

Name	Area (km^2)	Reservoir formation	Depth to top (m)	Average thickness (m)	NG	Porosity (%)	Density of the CO_2, kg/m^3	Storage capacity (Mt)
Iris	22.1	Albian	2600	100	0.5	20	650	29
Venus	16.55	Eocene	1000	100	0.5	20	550	18
Tomis	17.59	Albian	2700	144	0.5	20	650	33
Lotus	16.05	Albian	1523	135	0.5	20	650	28
Total capacity								108

The hydrocarbon fields selected for the Romanian scenario are fields that have been exploited for more than 30 years and discovered during the 1980s within the exploration campaign of the Black Sea, a Romanian exclusive economic zone. The three selected fields are currently operated by OMV Petrom. The published data are scarce.

Lebăda Est (Figure 2222–23) is an oil and gas deposit discovered in 1980. The field has 3 productive reservoirs in Albian (oil), Upper Cretaceous (oil) and Eocene (gas). All three reservoirs are of interest for storage, but the Albian formation could be considered as most suited. The structures have the shape of an asymmetric dome with a dip of 12–30° in the South and East and 60–70° in the North and North-East. The Albian reservoir, assumed the most suited for storage, comprises silicious and calcareous sandstones, micro conglomerates and conglomerates with a porosity of 17% and permeability of 82 mD[78]. The Upper Cretaceous (Turonian–Senonian) reservoir, represented by fissured limestones, with low permeability, is sealed by compact Campanian limestones. The Eocene

[78] Vangkilde-Pedersen, T., Anthonsen, K., Smith, N., Kirk, K., N, F., Van der Meer, B., Le Gallo, Y., Bossie-Codreanu, D., Wojcicki, A., Le Nindre, Y., Hendricks, C., Dalhoff, F., Christensen, N. “Assessing European capacity for geological storage of carbon dioxide – the EU GeoCapacityproject”, Energy Procedia 1 (2009) 2663–2670

reservoir, with a thickness of up to 300 m represented by an alternation of clayey limestones and compact marls, has Oligocene shales as a protective formation.

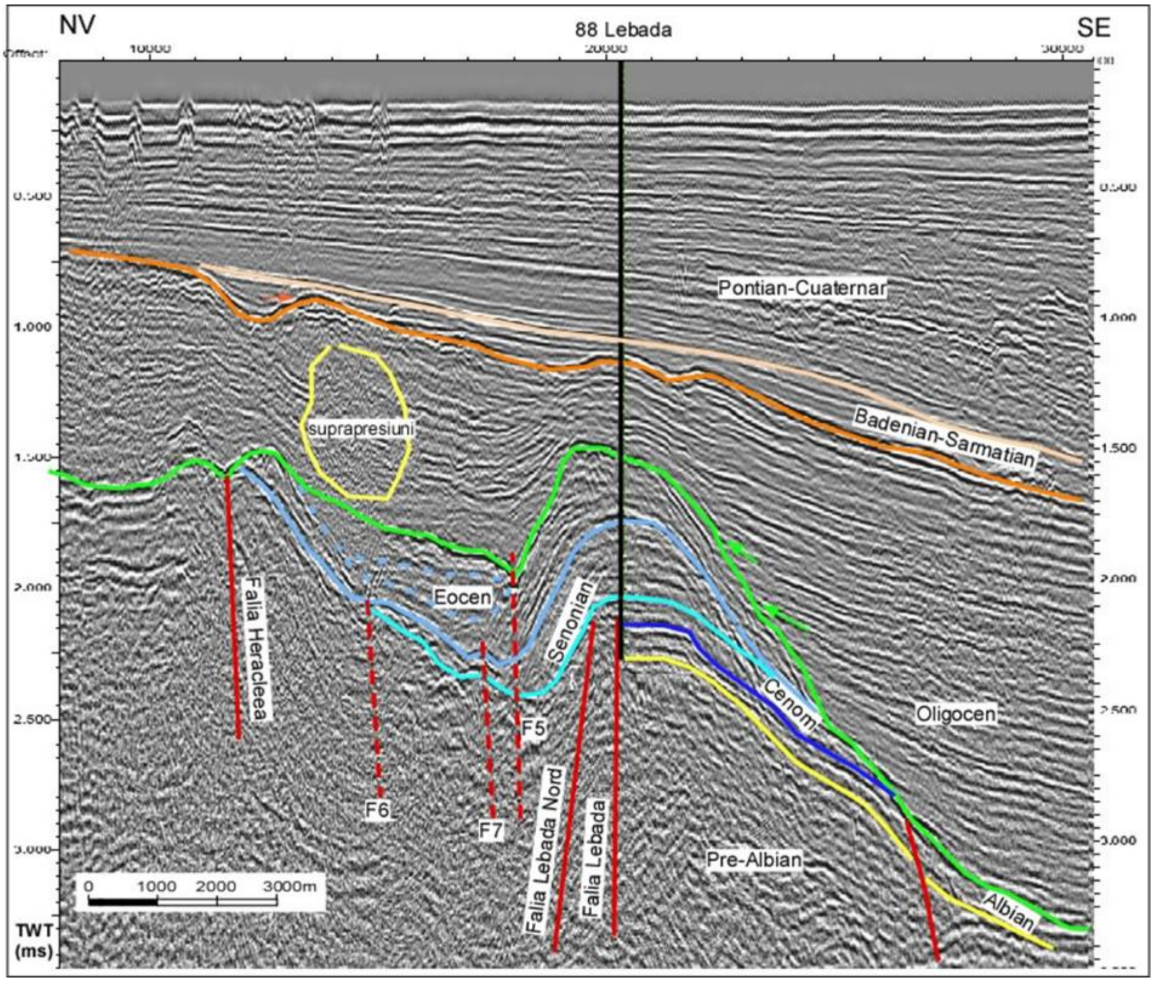


*Figure 22. Lebăda Est structure (after Țambrea, 2007*77*).*

Lebăda West Field (Figure 2323) was discovered in 1984 with oil in the Albian and Upper Cretaceous formations and gas in the Eocene formation. The most suitable reservoir for storage is in the Albian formation, divided into four porous units with good porosity and permeability. The reservoir mainly comprises fine quarzitic sandstones, gravelly limestones and microconglomerates[78].

The Sinoe field (Figure 2424) was discovered in 1988. The structural configuration is of an asymmetrical anticline-oriented WNW – ESE. The target reservoir is in the Eocene formation, divided into three porous and permeable sedimentary complexes. All these three complexes are composed of quarzitic sandstones with clay cement and clay intercalations.

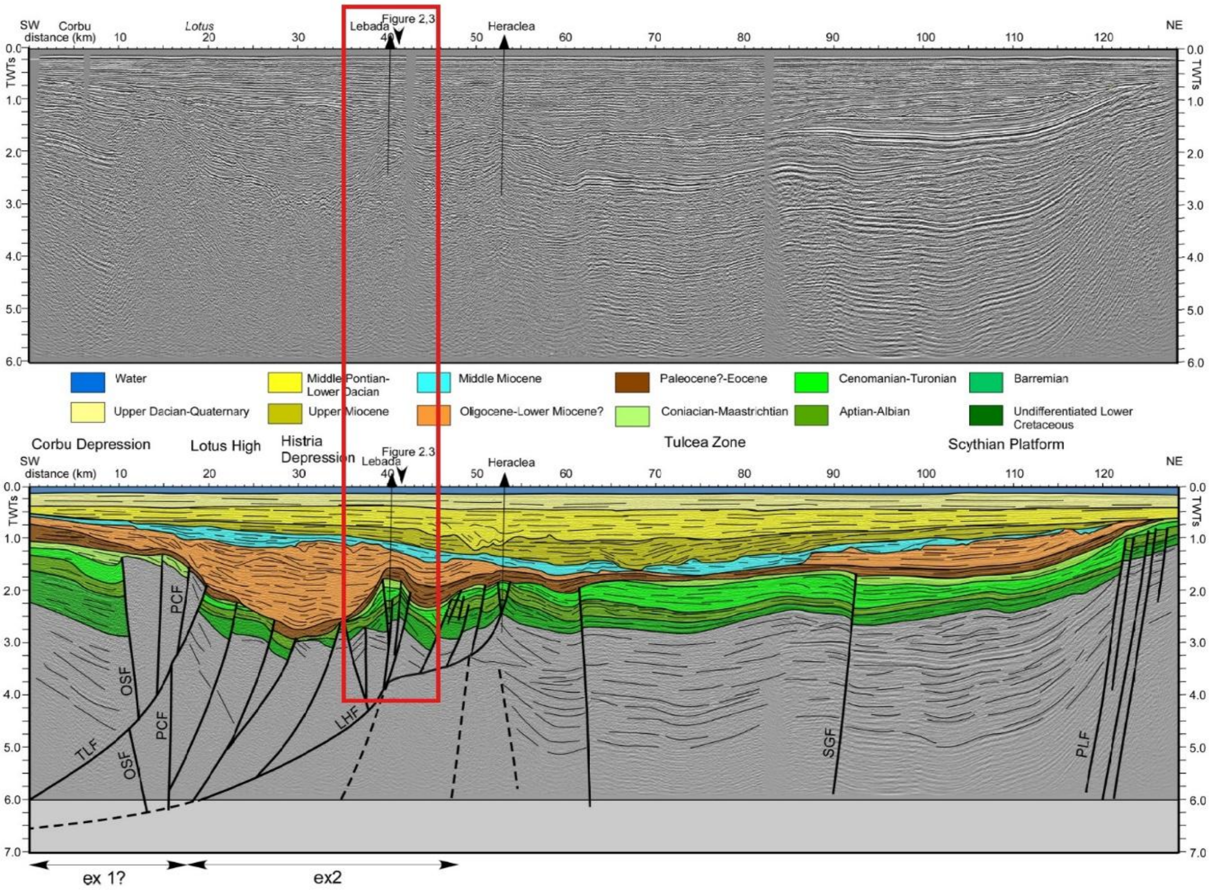


Figure 23. Lebăda structure (after Munteanu, 2012[79]).

For these hydrocarbon fields, storage capacity estimation has been made only for the oil reservoirs, the data for the gas reservoirs being considered unreliable. Because of poor data availability, a simple formula was used and implemented also in the EUGeoCapacity project:

$$M_{CO2} = \rho_{CO2} \times UR_p \times B$$

Where:
M_{CO2} is the storage capacity of the hydrocarbon field;
ρ_{CO2} is the CO_2 density at reservoir conditions;
UR_p is the proven ultimate recoverable oil or gas, the sum of cumulative production and the proven reserves;
B is oil or gas formation volume factor.
The parameters used for the estimation of capacity are presented in Table *22*22.

[79] Munteanu I., 2012. Evolution of the Western Black Sea: kinematic and sedimentological inferences from geological observations and analogue modelling. PhD Thesis, Utrecht University, 169 pp.

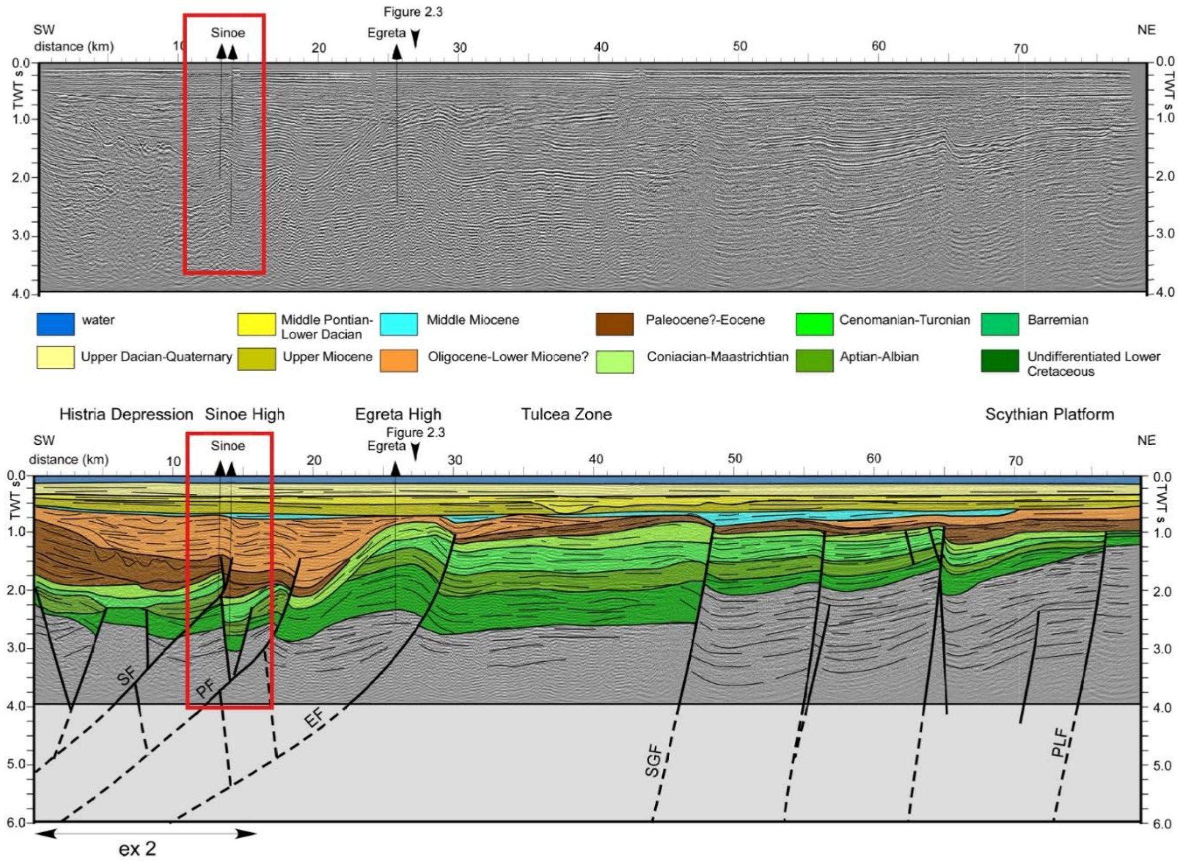


*Figure 24. Sinoe structure (after Munteanu, 2012*79*).*

Table 22. Estimation of storage capacity in depleted hydrocarbon fields.

Name of the structure	Area km²	Target reservoir	Average porosity %	Reservoir depth m	OOIPM m³	Recovery factor %	Ultimate recovery Mm³	Estimated thickness	Oil or gas formation volume factor	Storage capacity Mt
Lebăda Est	21.78	Albian	17	2300	8	40	50.8	30	1.2	25
Lebăda Vest	10.13	Albian	17	2400	8	40	52	25	1.2	25
Sinoe	11.89	Eocen	15	2000	3	40	32	35	1.2	9
Total capacity										59

From the potential storage sites in hydrocarbon fields, Lebăda Est seems to be the most feasible option in terms of capacity and status of depletion (being the oldest field brought into exploitation), so we can select this for further techno-economic analysis. This field can store more than half of 20 years of CO_2 to be captured from Călărași and Constanța cluster (approximately 41.4 Mt).

6.1.4 CO_2 Transport

The transport of captured CO_2 is designed as a multimodal involving onshore rail transport, fluvial ship transport and maritime transport for the final segment using pipeline, conventional ship and direct ship injection (Figure *25*25). Depending on the option chosen for the last transport segment, the Romanian main scenario can be divided into three scenarios. All these scenarios have a common design for the transport of CO_2 from Călărași, Medgidia, Constanța and Midia to a hub in the Midia port, from where the CO_2 will be sent using different options to the offshore storage sites.

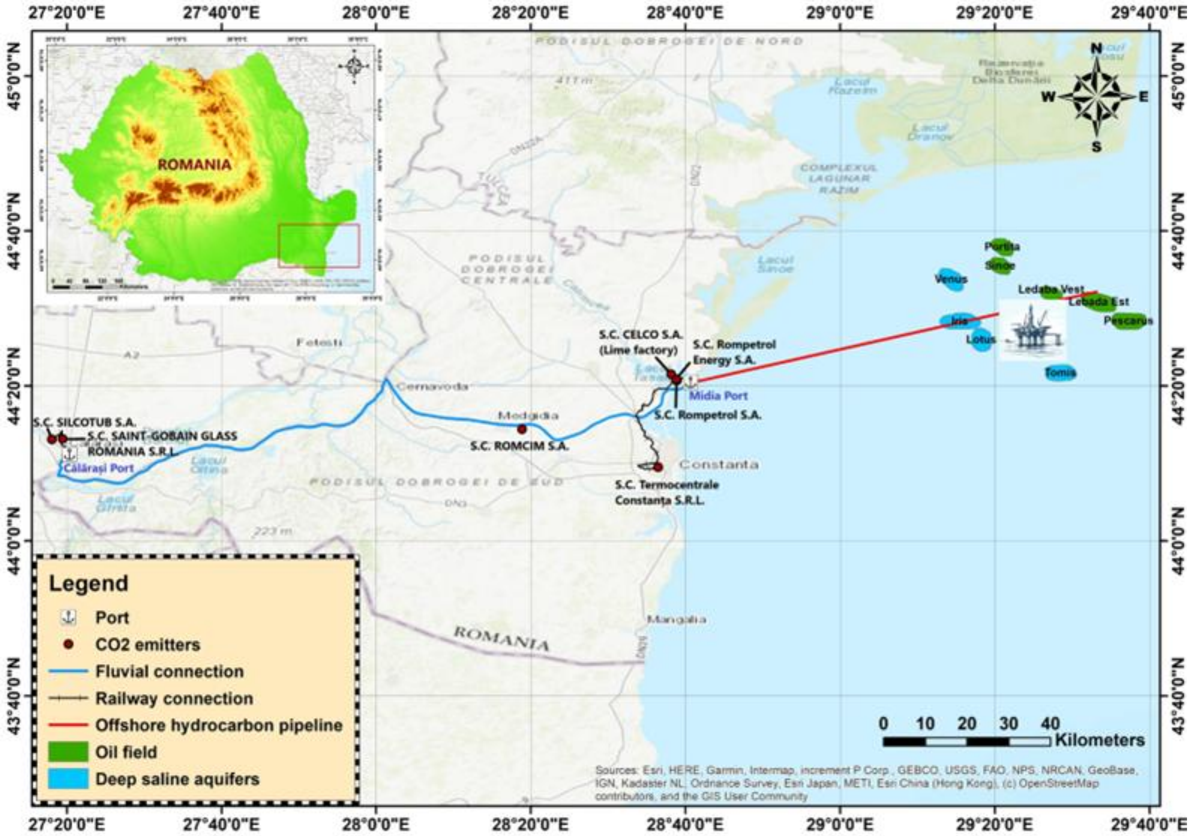


Figure 25. Schematic of CTS Romanian scenario showing the transport concept[80].

CO_2 captured from Călărași emitters can be transported by rail (10.4 km distance) up to an intermittent storage hub to be placed in Călărași commercial port (Figure *26*26). From this point, the captured CO_2 can be transported directly through the Danube and the upper branch of the Danube-Black Sea channel to a hub designed in Midia port (Figure *27*27).

The CO_2 captured from the Medgidia cement plant can be shipped directly from the Medgidia port to the Midia hub. The cement plant is located at approximately 1.5 km distance from the port. The CO_2 from Termocentrale Constanța can also be transported by rail (36.6 km distance) to the Midia hub and the CO_2 from the Celco lime factory at a 4 km distance (Figure *28*28). The other two emitters, the refinery and the energy plant, are, in fact, within Midia port, and short pipelines can be designed to connect them to the actual hub.

[80] A.-C. Dudu et al., "CTS Project: CO_2 transport and storage solutions in the Black Sea," Advances in Carbon Capture Utilization and Storage, Vol. 3, No. 1, –10, Jan. 2025, https://doi.org/10.21595/accus.2024.24736

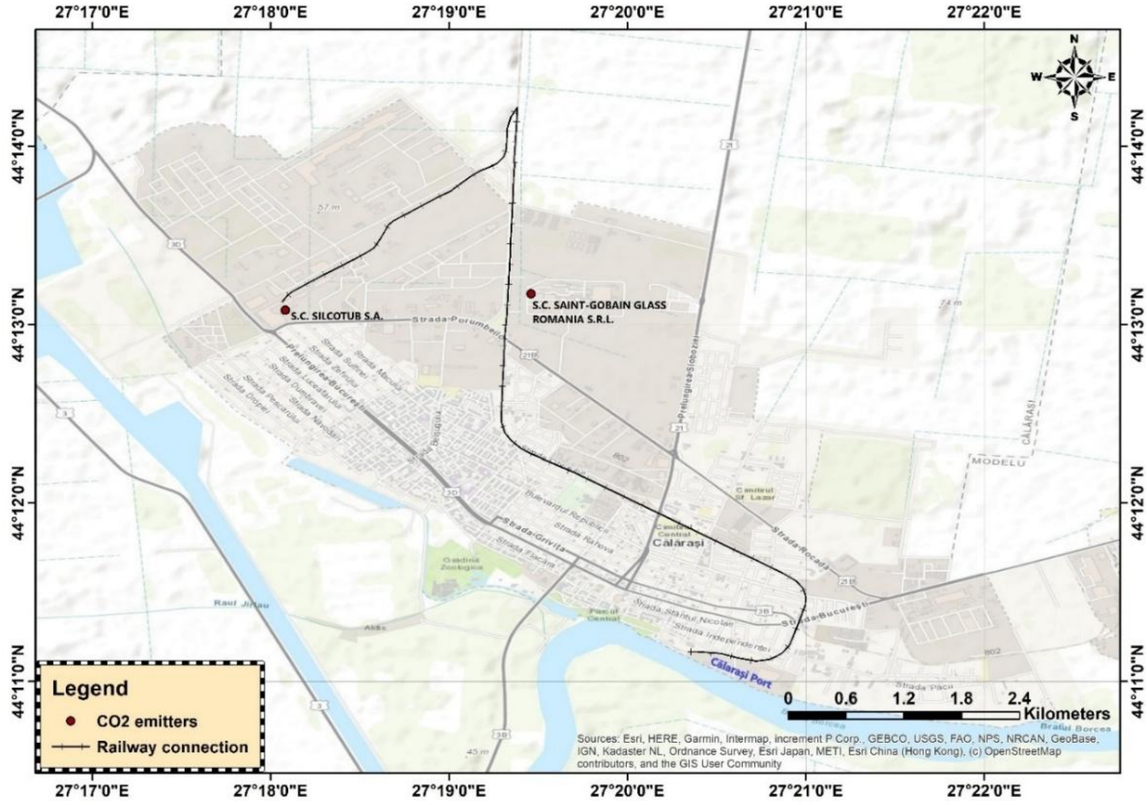


Figure 26. Possible rail connection from emitters to Călărași commercial port.

Figure 27. Fluvial connection from Călărași to Midia port.

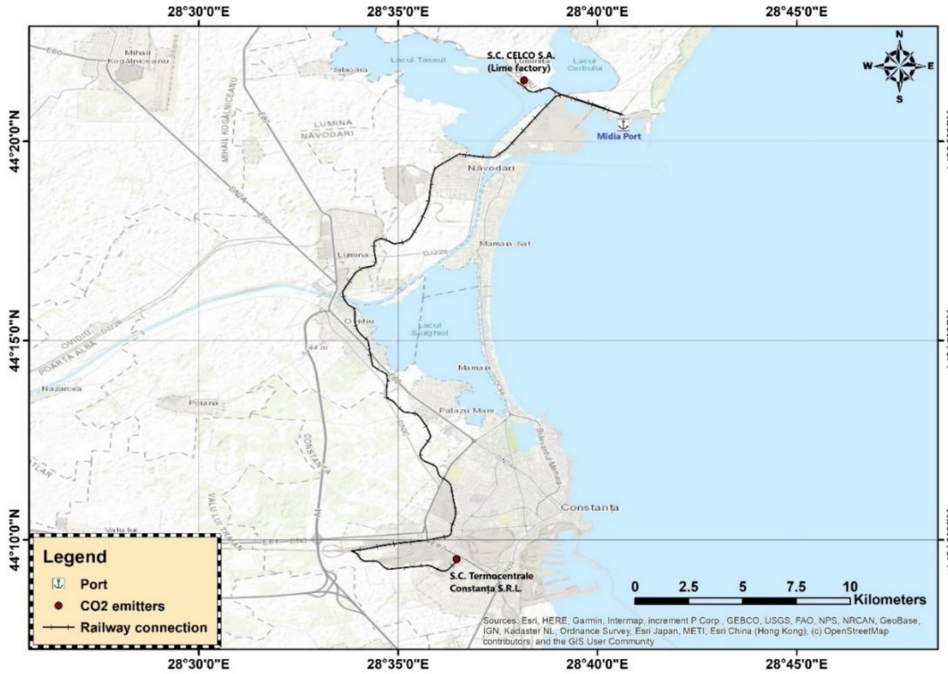


Figure 28. Rail connection to Midia port for Termocentrale Constanța and Celco lime factory.

From the Midia hub, as mentioned before, three options are designed and will be analysed in the CTS project as scenarios for the Romanian case.

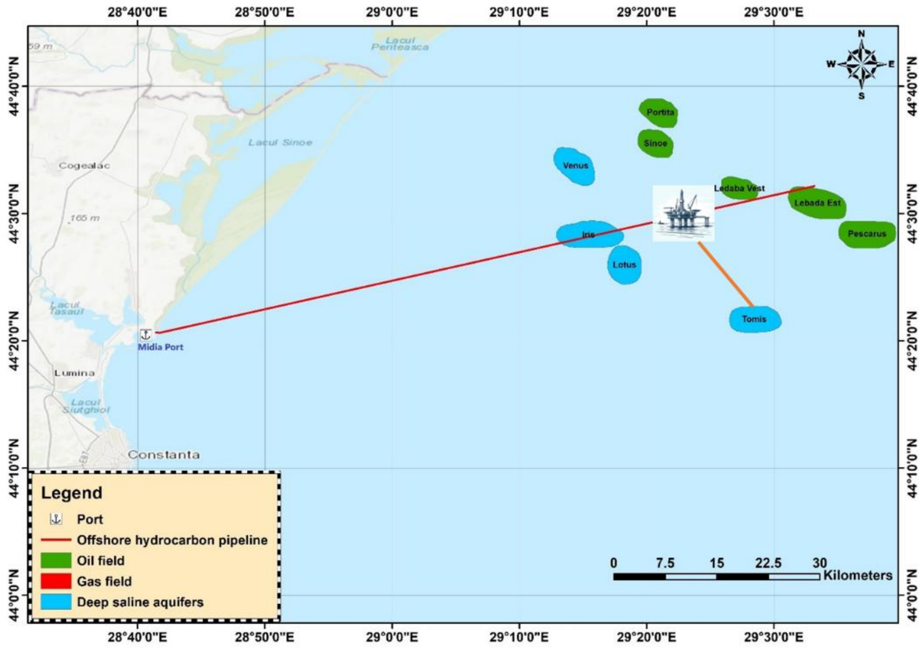


Figure 29. Offshore pipeline transport for Romanian CTS scenario.

Scenario 1: From the Midia hub, CO_2 will be transported through an offshore pipeline to a central platform, where the CO_2 will be distributed to the storage sites. The pipeline is designed to follow the corridor of the existing one that connects the Midia refinery and Gloria platform near the Lebăda Est field (Figure *29*29). From the Midia hub, the pipeline will go to an offshore platform from where the CO_2 will be distributed to the selected sites (e.g. Tomis and Lebăda Est).

Scenario 2: From the Midia hub, CO_2 will be loaded on conventional ships and transported to an offshore platform, where the CO_2 will be distributed to the storage sites (e.g., Tomis and Lebăda Est).

Scenario 3: From the Midia hub, CO_2 will be loaded on a ship specific for direct ship injection and injected directly into the selected storage reservoirs offshore.

Ports

Three ports are involved in the Romanian main scenario, each accommodating an intermediate storage hub from which the CO_2 can be loaded on fluvial ships or sent via maritime vessels or through an offshore pipeline to the storage sites. Călărași and Medgidia are fluvial ports on the Danube, and Midia is a maritime port.

In theory, Călărași has an industrial port meant to serve the steel plant, but this port has been inoperable for a long time. We have chosen Călărași commercial port as a potential hub since it is active, has space to accommodate new installations, and has good rail connectivity with the emitters considered in the scenario.

Medgidia port is located near the Romcim cement plant and is used to transport products from the plant. It is logical that, due to the high level of emissions, a hub should be placed in the port or near the port.

Midia port is an important industrial port in the Black Sea with a direct connection to the offshore hydrocarbon fields that could be used as a corridor for CO_2 transport to offshore storage sites. Midia Port also has good rail connectivity.

Onshore transport

Onshore transport from emitters to the central hub, Midia, will be done via rail, short pipelines and river. The onshore transport options are presented in Table *23*23.

Table 23. Onshore transport options for the Romanian scenario.

Cluster	Emitter/hub	Port/hub	Transport type	Distance, km
Călărași	S.C. SILCOTUB S.A. Punct de lucru Călărași	Călărași	rail	10.40
	S.C. SAINT - GOBAIN GLASS ROMÂNIA S.R.L.	Călărași	rail	6.98
	Călărași hub	Midia	river	140
	Total per Călărași cluster			157.38
Constanța	Romcim Medgidia	Medgidia	Road/short pipeline	1.50
	Medgidia	Midia	river	36
	S.C. CELCO S.A.	Midia	rail	4
	S.C. Termocentrale Constanta S.R.L.	Midia	rail	36.6
	S.C. Rompetrol Rafinare S.A. – Petromidia	Midia	Short pipeline	1
	Rompetrol Energy S.A. (former Termoelectric facility Midia S.A.)	Midia	Short pipeline	1
	Total per Constanța cluster			80.1
Total				237.48

6.1.5 Summary

The Romanian scenario was initially derived from the scenario built for implementing CCUS in the Galați region within the STRATEGY CCUS project. Due to the industrial decline of the region and because an important CO_2 emitter from Tulcea is closing, under CTS, new emitters with active businesses have been taken into consideration as CO_2 capture sources. The main scenario involves the capture of CO_2 from two clusters, Călărași and Constanța and storage in the offshore structures (depleted hydrocarbon fields and deep saline aquifers) in the Black Sea. CO_2 will be transported by rail and by river to the main hub in Midia port (Table 24).

Approximately 2.18 Mt of CO_2 is produced by the emitters considered in the scenario. Considering a capture rate of 95%, a total of 2.07 Mt will be captured from both clusters (2 facilities for Călărași and five facilities for Constanța), transported via rail to inland ports and then via the Danube and by rail to the main hub from Midia, from which it will be shipped via conventional ships or by direct ship injection to offshore structures with a maritime shipping distance of 72.1 km. The rail distance to ports varies from 10.4 km (from S.C. SILCOTUB S.A. to Călărași port) to 36.6 km (from S.C. Termocentrale Constanta S.R.L. to Midia port).

For the Călărași cluster, approximately 0.15 Mt CO_2 is produced by two plants. Considering a capture rate of 95% for the two plants, a total of 0.14 Mt CO_2 will be captured and transported by rail to Călărași port (10.4 km) and then by river Danube 140 km to Midia hub and then by ship or pipeline on a distance of 72.1 km to offshore storage sites.

For the Constanța cluster, 2032535 t (approximately 2.03 Mt) CO_2 is produced by five plants. Considering a capture rate of 95%, 1.93 Mt CO_2 will be captured and transported to Midia hub by rail (4 km for S. C. CELCO S.A, 36.6 km for S.C Termocentrale Constanța S.R.L.), by a river (36 km from Medigdia to Midia) or by short pipelines (approximately 1.5 km from Romcim Medigidia cement plant to Medgidia port and inside 1 km for emitters located very close to Midia hub - S.C. Rompetrol Rafinare S.A. – Petromidia and Rompetrol Energy S.A.). From the Midia hub, the CO_2 will be transported 72.1 km via ship or pipeline to offshore storage sites.

Table 24. CO_2 emissions produced, captured, used, and transported in the Black Sea scenario.

Cluster to Port	Number of plants	CO_2 produced Mt/y	CO_2 captured Mt	CO_2 transported Mt	Transport distance to port km	Ship distance from port to storage site km	Storage site
Călărași to Midia	2	0.15	0.14	0.14	157.38	75	Tomis
Constanța to Midia	5	2.03	1.93	1.93	80.1	72/75	Tomis/Lebăda Est
Total	**7**	**2.18**	**2.07**	**2.07**	**237.48**	**144.2**	**2**

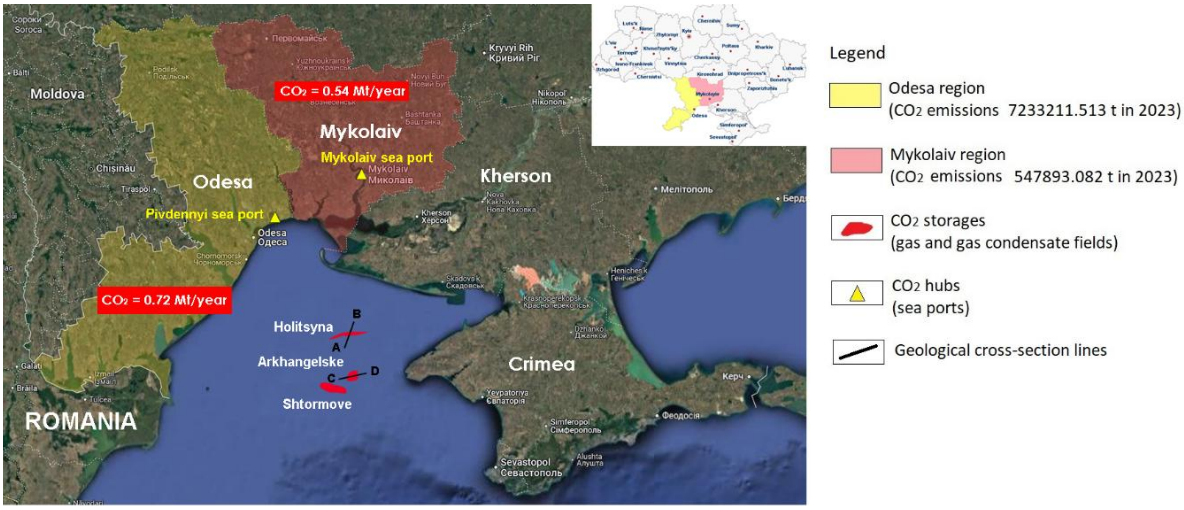
The total storage capacity available, estimated at the theoretical level (based solely on public data), is 167 Mt, and the total CO_2 to be captured from clusters for 20 years is 41.4 Mt of CO_2. Two sites that could be selected for further techno-economic analysis, Tomis and Lebăda Est, have a cumulated storage capacity of 58 Mt, more than enough to store 20 years of 2.07 Mt/year, 41.4 Mt.

6.2 Ukraine

6.2.1 Introduction

The Ukrainian basic scenario encompasses both onshore and offshore components. The onshore focus includes the Odesa and Mykolaiv regions with CO_2 emissions and key hub locations. At the same time, the offshore segment covers the Ukrainian exclusive economic zone in the Black Sea, where potential CO_2 storage sites have been identified (Figure *30*30). On June 25, 2024, Ukraine approved its National Energy and Climate Plan (NECP) for 2030, setting an ambitious path toward climate neutrality by 2050 for the energy sector and by 2060 for the entire country. The NECP outlines that achieving net-zero emissions in electricity and heat production before 2050 will rely on a combination of bioenergy and CCS technologies. Given the current structure of Ukraine's generation and industry sectors and the long transition cycles required for green economic transformation, accelerated CCS deployment is essential for decarbonisation. The existing research and technological base for CO_2 capture and storage technologies in Ukraine is at an early stage, so stimulating research in this field and implementing relevant technologies are significant elements in reducing emissions in the near future. Furthermore, the Energy Strategy of Ukraine 2050 envisions deploying CCS projects, potentially repurposing existing gas infrastructure as part of decarbonisation initiatives. Despite these efforts, Ukraine must establish clear policies for geological and economic assessments to evaluate the sustainability of CO_2 storage sites and to streamline the permitting and licensing processes for CO_2 storage projects, ensuring adherence to environmental and safety standards at the national level.

Figure 30. Map with target regions, potential CO_2 hubs and storage facilities in Ukraine for the CTS project.



6.2.2 CO_2 Emissions

Ukraine is the largest country in Eastern Europe, with a total area of 603,628 km^2 and a population of more than 38 mln. people[81]. According to the Inventory of GHG Emissions for 1990–2021, GHG emissions (CO_2, CH_4, N_2O, Fluorinated gases: HFCs, PFCs, SF_6, NF_3) amounted to 341.5 million tonnes of CO_2-equivalent (including the LULUCF-Land Use, Land-Use Change and Forestry sector) in 2021. This is 62.5% lower than 1990 levels but 7.5% higher than 2020 (

*Table 12*25).

[81] https://www.worldometers.info/world-population/ukraine-population/

Table 25. GHG Emissions, Mt CO_2-eq[82]

Gas	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021	Current year compared to base year, %
CO_2 (excluding LULUCF)	706.2	390.1	285.7	313.5	294.4	223.8	234.0	223.1	231.7	221.9	206.8	210.2	-70.2
CH_4	182.9	139.1	118.3	102.8	84.9	61.6	66.4	64.2	67.9	70.1	72.0	71.5	-60.9
N_2O	53.6	33.1	24.1	25.9	27.6	33.2	36.5	35.1	39.0	40.6	38.1	43.8	-18.4
HFCs*	NO	NO	15.7	285.1	743.9	801.6	921.4	1049.3	1395.8	1685.0	1751.5	1901.0	100.0
PFCs*,**	235.8	178.1	115.7	142.3	26.7	NO	NO	NO	NO	NO	NO	NO	-100.0
SF_6*	0.0	0.1	0.4	4.5	9.7	19.6	24.4	28.6	33.4	38.8	43.4	48.9	641194.7
NF_3*	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	-
Net CO_2 from LULUCF	-31.6	-32.4	-23.2	-9.3	-9.2	19.5	24.2	13.3	24.7	23.1	-1.1	14.0	-144.4
CO_2 (including LULUCF)	674.6	357.6	262.5	304.3	285.1	243.3	258.2	236.4	256.4	245.1	205.8	224.2	-66.8
Total (excluding LULUCF)	942.8	562.1	427.9	442.4	407.3	319.2	337.6	323.3	339.8	334.1	318.0	327.3	-65.3
Total (including LULUCF)	911.4	530.0	405.0	433.5	398.3	338.9	362.0	336.7	364.7	357.4	317.6	341.5	-62.5
Total (excluding LULUCF), including indirect CO_2	942.8	562.1	427.9	442.4	407.3	319.2	337.6	323.3	339.8	334.1	318.0	327.3	-65.3
Total (including LULUCF), including indirect CO_2	911.4	530.0	405.0	433.5	398.3	338.9	362.0	336.7	364.7	357.4	317.6	341.5	-62.5

*emissions quoted in kt CO_2-eq.

** there are no PFC emissions, as cooling agents containing the gas were not imported in 2011-2021

The Ukrainian scenario is assessed at a regional scale and includes CO_2 emissions from two southern regions - Odesa and Mykolaiv- with significant industrial development and good seaport infrastructure. There are over 200 small emitters in each target region, collectively reporting total emissions of 1.26 Mt. These emissions are included in the CTS project scenarios, depending on how many large CO_2 emitters can implement CO_2 capture in reality. Other seaside regions (Kherson and Crimea) were currently excluded from analysis due to the agricultural focus of economics and the significant impact of the ongoing war, causing doubts about data quality. The western Crimean area can potentially expand this study in the following research.

Data and source analysis revealed that there is currently no unified database for reporting CO_2 emissions by enterprises in Ukraine. Due to the geopolitical situation, access to specific data has been restricted since February 2022[83]. While Environmental Reports from Region[84] highlighting that major emissions with the largest share of GHG emissions are publicly available, the lack of specific data for CO2 emission point sources limits the Ukrainian scenario of analysing emissions in two regional clusters (hubs). The Ukrainian scenario is based on CO_2 data from 2023 available at the State Statistics Service of Ukraine.

6.2.2.1 Odesa Region

Odesa is a region in southwestern Ukraine located along the northern coast of the Black Sea. It is Ukraine's largest region, covering an area of 33,310 km², accounting for approximately 5.5% of its total land area. Odesa has a population of around 2.4 million (2022) and shares a southern border with Romania. Odesa region is a highly industrialised area crucial to Ukraine's national economy. It hosts various industries, including oil refining, machinery manufacturing and maintenance, metallurgy, metalworking, chemical and petrochemical production, food processing, and light industry. In 2021,

[82] https://unfccc.int/documents/628276
[83] https://zakon.rada.gov.ua/go/263-2022-%D0%BF
[84] https://mepr.gov.ua/diyalnist/napryamky/ekologichnyj-monitoryng/ekologichni-pasporty/

the Odesa region accounted for 2.6% of Ukraine's total industrial output, ranking 10th among the country's regions (Table 2626).

Table 26. CO_2 emissions produced by stationary sources in the Odesa region.

Year	Produced CO_2 emissions Mt/y	Time trend
2021	1.41	89.2% to 2020
2022	0.69*	49.3% to 2021
2023	0.72*	104% to 2022
source: State Statistics Service of Ukraine **- Data exclude the territories which are temporarily occupied by the Russian Federation and part of territories where the military actions.*		

6.2.2.2 Mykolaiv Region

Mykolaiv is a region in southern Ukraine along the Black Sea coast, covering an area of 24,598 km², which is 4.08% of Ukraine's territory. As of 2022, the population is approximately 1.09 million. The regional centre is Mykolaiv city. Mykolaiv region is represented by a powerful multi-branch industry, well-developed agricultural and industrial complex (machine-building industry, including shipbuilding, non-iron metallurgy, food and light industries), transportation network and sea-port economy (Table 277).

Table 27. CO_2 emissions produced by stationary sources in the Mykolaiv region.

Year	Produced CO_2 emissions, Mt/y	Time trend
2021	2.13	101.7% to 2020
2022	0.52*	24.5% to 2021
2023	0.54*	104.8% to 2022
source: State Statistics Service of Ukraine **- Data exclude the territories temporarily occupied by the Russian Federation and part of territories where military actions are taken.*		

6.2.3 CO_2 Storage Sites

6.2.3.1 Storage Sites Description

CO_2 will be transported to offshore storage sites in the Black Sea, where geological formations are suitable for long-term sequestration. The reservoirs have been identified in depleted gas and gas condensate fields (Holitsyna, Arkhangelsk, Shtormove) confined to the Karkinite-North Crimean depression. Gas and gas condensate reservoirs, which are considered as potential CO_2 storages, primarily referred to as Oligocene-Lower Miocene (Maykop series) and Lower Palaeocene formations consist of clay-rich, carbonate (limestones, marls) and terrigenous (sandstones) sediments with porosity ranges from 20 to 30% at depth from 900 m and up to 2500 m[85] (*Table 28*8).

[85] V. Mykhailov, S. Vyzhva, V. Zagnitko, V. Ogar, O. Karpenko, I. Onischuk, S. Kurovets, M. Gladun and O. Andreeva, "Unconventional sources of hydrocarbons of Ukraine: monograph. In eight books. Southeastern oil and gas bearing region (in Ukrainian)," vol. 3, Kyiv University Publishing and Printing Center, 2014.

Holitsyna Storage Site

Holitsyna gas condensate field is the first field on the Black Sea, discovered in 1971 and located approximately 30–40 m water deep, 70 km from Chornomorske (Crimea) and 130 km from Odesa city[86]. The geological structure comprises sediments from the Lower Paleocene, Eocene and Oligocene (Maykop series). Eocene clay layers seal the Paleocene section of the structure.

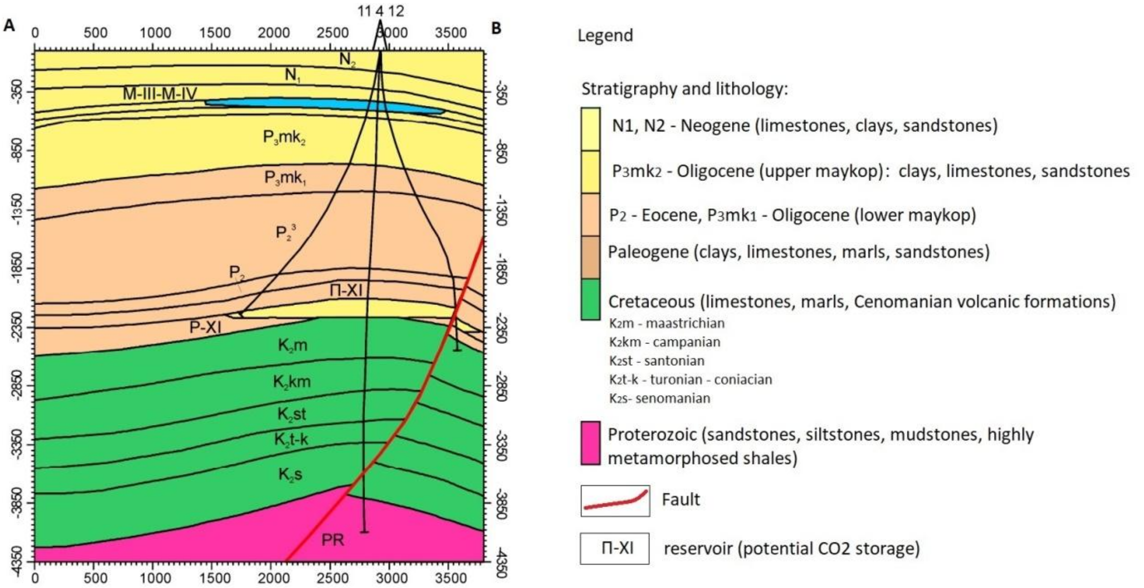


Figure 31. Geological cross-section[87] through line A-B of Holitsyna field. The location is shown in Figure 30.

Gas condensate reservoir (П-XI), which is considered a potential CO_2 storage, includes organogenic-detrital and fractured pleiomorphic limestones of the Lower Paleocene, forming an elongated anticlinal fold with an area of 43.17 km^2 (*Figure 31*31).

Arkhangelsk Storage Site

Arkhangelsk gas field, discovered in 1965, is an offshore field located in the north-western part of the Black Sea, 66 km from Chornomorske in Crimea[88]. CO_2 storage (M–V) is confined to the reservoir at a depth of 915 m with a total area of 28.6 km^2 and is composed of sand-siltstone layers within the clay strata of the Maykop series[89] (Oligocene) (Figure 3232). Gas production began in 1992.

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[86] D. E. Makarenko, "Holitsyna gas condensate field," [Online]. Available: https://esu.com.ua/article-25252. [Accessed 14 December 2024].

[87] O.P. Petrovskyi, B.B. Hablovskyi, N.S. Ganzhenko, T.O. Fedchenko, Justification of the possibility of mapping oil and gas prospective objects in the conditions of the northwestern part of the black sea shelf on the base of seismogravity modeling, 2009. http://elar.nung.edu.ua/bitstream/123456789/2006/1/658p.pdf

[88] D. E. Makarenko, "Arkhangelske gas field," [Online]. Available: https://esu.com.ua/article-44753. [Accessed 14 December 2024].

[89] R. Kondrat, M. Kharitonov, O. Kondrat and P. Melnychuk, "Features of the development and operation of the Arkhangelske gas field and ways of increase efficiency gas production and gas extraction coefficient," *Exploration and development of oil and gas fields,* no. 2, pp. 66-69, 2006.

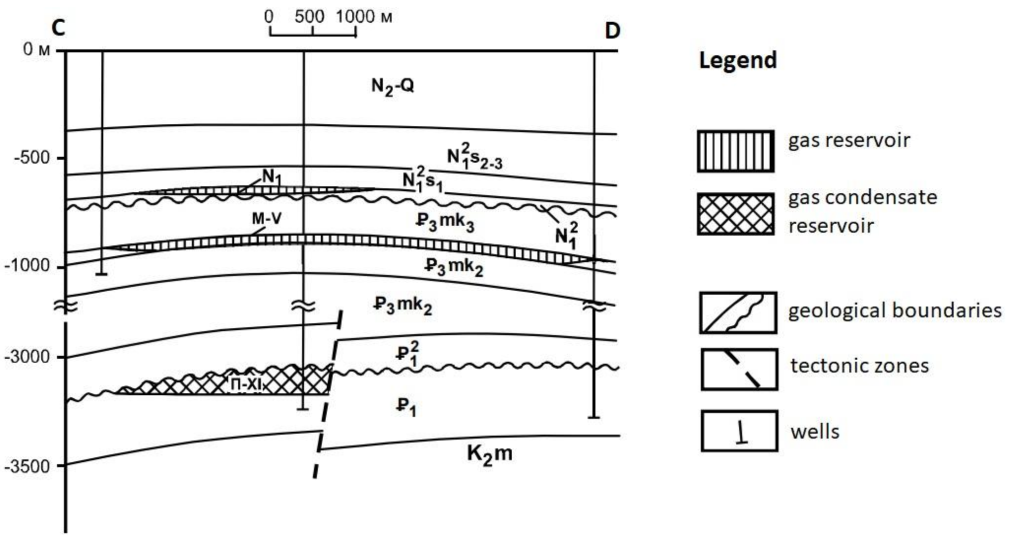

Figure 32. Geological cross-section[90] through line C-D of the Arkhangelsk field. The location is shown in Figure 30 (K_2m – Cretaceous period, Maastrichtian age, ₽$_1$ – Paleocene, ₽$_3$ – Oligocene (mk – Maykop series), N_1 – Miocene (s - sarmat), N_2 – Pliocene, Q – Quaternary).

Shtormove Storage Site

Shtormove gas condensate field is 82 km southwest of Chornomorske (Crimea) in the Black Sea. Reservoir П-XI, as potential CO_2 storage, presented microcrystalline fractured limestones of the Lower Paleocene with 30% porosity[91]. The total unit area is 20.25 km^2 at a depth of 986 m. The seal is Eocene marls and clays (Table 28).

Table 28. Geological and technical parameters of hydrocarbon fields in the Black Sea in Ukraine.

Field name	Age	Target reservoir	Area km²	Reservoir depth m	Average reservoir thickness m	Average porosity %	Permeability mD	Reservoir lithology	Caprock
Holitsyna	Lower Paleocene	П-XI reservoir	43.17	2155	80	15	1.5	Carbonate (limestones, marls) and terrigenous (sandstones) sediments	Clay
Arkhangelsk	Oligocene -Lower Miocene	Maykop (M-V reservoir)	28.6	915	36	26	57.8	Sandstones and siltstones	Clay
Shtormove	Lower Paleocene	П-XI reservoir	20.25	986	85	17	2.3	Limestones	Clay

6.2.3.2 CO_2 Storage Capacity

Gas production has been taking place since the 1980-90s. The preliminary theoretical CO_2 storage capacities were estimated using the following approach[92] (*Table 29*9):

[90] http://www.geol.univ.kiev.ua/lib/mono_USHU/3_South_Region.pdf

[91] M. Pavlyuk and M. Yakovenko, "Oil and gas bearing potential sea areas of the East European Platform," *Geology and minerals of the World Ocean,* no. 1, pp. 32-46, 2019.

[92] Vangkilde-Pedersen, T., Anthonsen, K., Smith, N., Kirk, K., N, F., Van der Meer, B., Le Gallo, Y., Bossie-Codreanu, D., Wojcicki, A., Le Nindre, Y., Hendricks, C., Dalhoff, F., Christensen, N. (2009). Assessing European capacity for geological storage of carbon dioxide – the EU GeoCapacity project, Energy Procedia 1 (2009) 2663-2670.

$$MCO_2 = \rho CO_2 r \times Rf \times (1 - F_{ig}) \times OGIP \times BgM$$

where: ***MCO_2*** – estimated CO_2 storage capacity (mass), **Mt** – millions of tonnes, **$\rho CO_2 r$** – CO_2 density at reservoir conditions (kg/m^3), **Rf** – Recovery factor (percentage of pore space usable for CO_2 storage, ***OGIP*** - Original Gas in Place at surface conditions (volume, typically in standard cubic meters or SCF), **Bg** – Gas formation volume factor (dimensionless), representing the ratio of reservoir volume to surface volume of gas, **F_{ig}** - fraction of injected gas (proportion of gas already in place that remains post-injection).

Table 29. Parameters and potential for CO_2 storage capacity in Mt in the studied gas and gas condensate fields in the Black Sea in Ukraine.

Field and reservoir name	$\rho CO_2 r$, kg/m^3	Rf	OGIP, Mm^3	Bg	F_{ig}	MCO_2, Mt
Holitsyna (П-XI reservoir)	700	0.2	11,896	0.004	0.5	3.33
Arkhangelske (M-V reservoir)	600	0.2	5413	0.006	0.5	1.95
Shtormove (П-XI reservoir)	620	0.2	16,574	0.004	0.5	4.11
Total MCO_2, Mt						9.39

The total theoretical estimated CO_2 storage capacity in 3 studied fields is about 9.39 Mt. Incomplete subsurface data lead to uncertainty of CO_2 storage capacity. Currently, the fields are listed among the oil and gas production facilities on the Black Sea shelf that have been temporarily under Russian control[93] since 2014. Operational scenarios and development plans can proceed once the geopolitical situation is resolved.

6.2.4 CO_2 Transport

There are three options for transporting CO_2 to storage facilities that were evaluated: (1) pipelines, (2) conventional ships and (3) NEMO ships.

6.2.4.1 Ports

Odesa, Pivdennyi and Mykolaiv seaports are being considered as strategic CO_2 hubs.

Odesa Seaport 94 is considered a local hub for emissions from the Odesa region. Strategically located in the southwestern part of Odesa Bay, in the north-western Black Sea. The port features a 9-kilometre mooring line with 54 berths, accommodating vessels with depths of up to 14 m. Considering that the port is in Odesa, its use as a CO_2 hub may present challenges due to environmental regulations and the permitting process. As a result, the Pivdennyi seaport is a more suitable alternative.

Pivdennyi seaport[94] is Ukraine's largest and deepest port, strategically positioned as a primary hub for managing CO_2 emissions from the Odesa region. The seaport boasts 30 jetties with a total length of 5.5 km and a maximum depth of 20 m, making it capable of accommodating large ocean-going vessels.

The port's advanced infrastructure includes deep-water berths equipped with state-of-the-art handling systems such as high-capacity gantry cranes, bulk cargo conveyors, and specialised facilities for liquid cargo operations. Additionally, Pivdennyi is integrated with efficient rail and road networks,

[93] https://www.kmu.gov.ua/npas/pro-zatverdzhennia-pereliku-obiektiv-naftohazovydobuvannia-v-mezhakh-kontynentalnoho-shelfu-ukrainy-iaki-ie-okupovanymy-rosiiskoiu-federatsiieiu-945-230822
[94] https://www.port-yuzhny.com.ua/

enabling seamless multimodal logistics. It also features extensive storage capacities, including refrigerated and dry warehouses, enhancing its CO_2 transport and storage hub potential.

Mykolaiv seaport[95] is considered the central hub for emissions from the Mykolaiv region and ranks among Ukraine's top three ports in cargo trans-shipment volume. Recognised as an enterprise of strategic importance to the national economy, the port plays a critical role in regional and national logistics.

The port can accommodate vessels up to 215 m long with drafts of up to 10.5 m, making it suitable for medium to large-scale maritime operations. It features 15 operational berths with a total length exceeding 3 km and a maximum depth of 11.2 m. The port's infrastructure includes advanced cargo handling systems such as mobile harbour cranes, conveyor systems, and bulk handling facilities. Additionally, it is equipped with extensive storage capabilities, including covered warehouses and open cargo areas, ensuring efficient handling of diverse cargo types, including bulk, liquid, and general cargo. Its integration with rail and road networks further enhances its capacity as a reliable CO_2 hub.

6.2.4.2 Pipelines

<u>Scenario-1. Combined onshore and offshore pipeline construction model</u>

This scenario explores the construction of CO_2 transportation combined onshore and offshore pipelines extending from Pivdennyi and Mykolaiv seaports to potential offshore storage sites in the Black Sea (

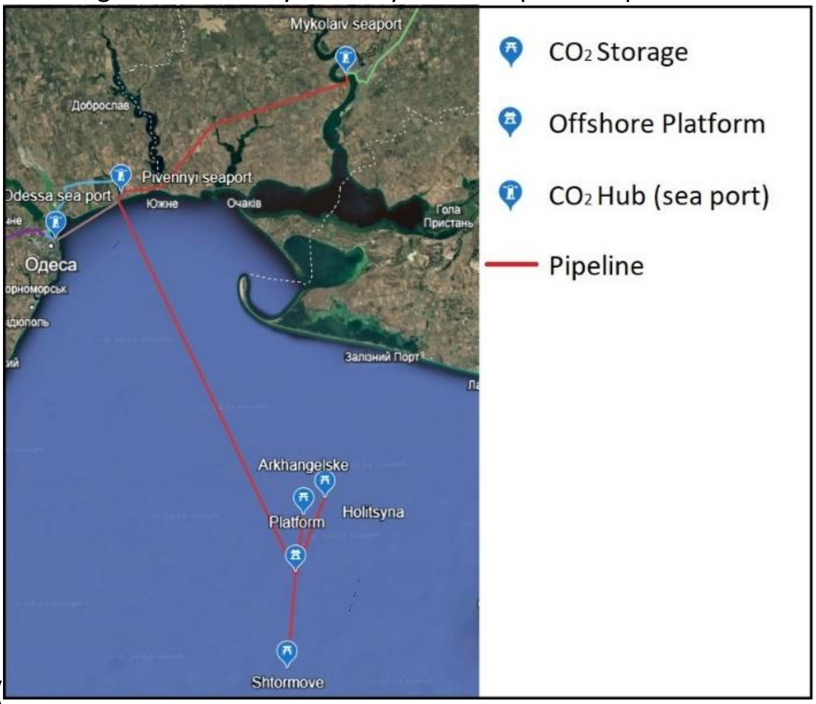

Figure 33. Pipeline construction model from Pivdennyi and Mykolaiv seaports to potential offshore storage sites in the Black Sea.

[95] https://mmtp.com.ua/

Odesa Region

For the Odesa region, the proposed pipeline would extend from Pivdennyi seaport to a simulated offshore platform (here and after - Platform) in the Black Sea. The Platform would be strategically positioned midway between identified gas and gas condensate fields, considered potential CO_2 storage sites.

33).

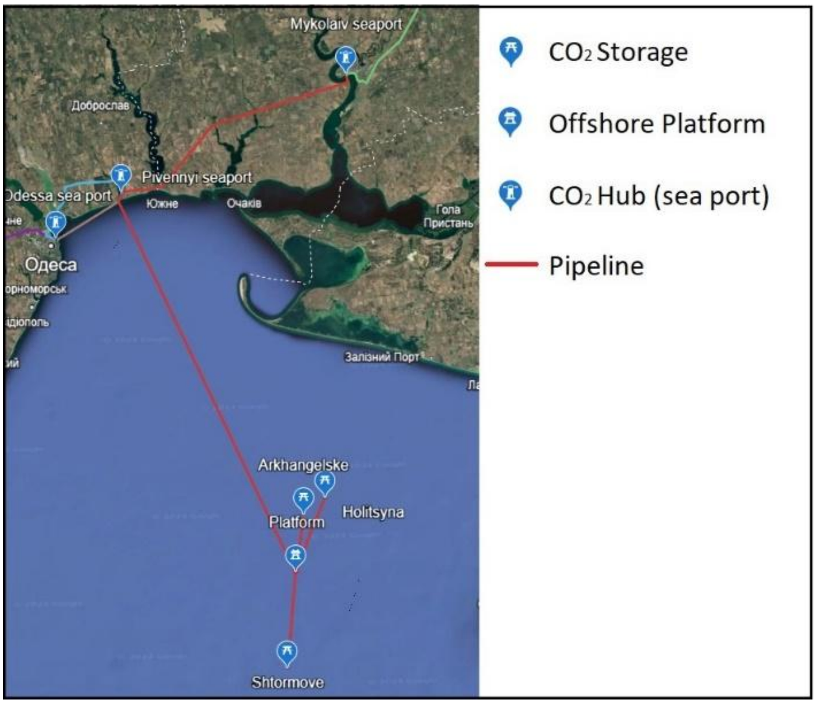

Figure 33. Pipeline construction model from Pivdennyi and Mykolaiv seaports to potential offshore storage sites in the Black Sea.

Odesa Region

For the Odesa region, the proposed pipeline would extend from Pivdennyi seaport to a simulated offshore platform (here and after - Platform) in the Black Sea. The Platform would be strategically positioned midway between identified gas and gas condensate fields, considered potential CO_2 storage sites.

Mykolaiv Region

The Mykolaiv seaport, located on the left bank of the Southern Bug River, presents additional logistical challenges. To connect directly to the Black Sea, the pipeline must traverse the Buzko-Dnipro-Limansky Canal, which passes through the Dnipro Estuary and the Southern Bug River. This route would significantly increase construction costs due to the complexity of building through aquatic and estuarine environments.

The onshore part of pipelines is optimised for realistic routes. However, land use would be one of the main risks in the scenario. Alternatively, an offshore or combined onshore/offshore pipeline between Pivdennyi and Mykolaiv seaport can be considered.

To optimise cost-efficiency and technical feasibility, a hybrid approach is recommended:

1. **Onshore Pipeline**: Construct a pipeline from Mykolaiv seaport to a coastal hub at Pivdennyi seaport in the Odesa region.
2. **Offshore Pipeline**: Extend the pipeline from the Pivdennyi seaport to the Platform in the Black Sea.

This combined approach leverages the existing infrastructure and deep-water capabilities of Pivdennyi, minimising the higher costs associated with direct offshore construction from Mykolaiv. Additionally, it could simplify the permitting and construction process while ensuring efficient transport of CO_2 to the designated offshore storage site. By centralising the offshore connection at Pivdennyi, the model achieves greater economic and logistical efficiency, reducing redundant infrastructure and maximising resource utilisation. The total proposed pipeline length is 294.6 km (Table 30).

Table 30. Transport distance by pipelines from ports to Platform and from Platform to storage sites in the Black Sea within the Ukrainian scenario.

Number	Distance description	Pipeline proposed length, km
1	Pivdennyi Seaport- Offshore Platform	133.6
2	Mykolaiv seaport- Pivdennyi seaport (onshore)	86.4
3	Platform – Holitsyna storage	26.5
4	Platform – Archangelske storage	18.2
5	Platform – Shtormove storage	29.9
	Total	294.6

6.2.4.3 Ship Routes

Several CO_2 transportation routes are considered in the Ukrainian scenarios, including traditional ship (Scenario II) and the NEMO solution (Scenario III).

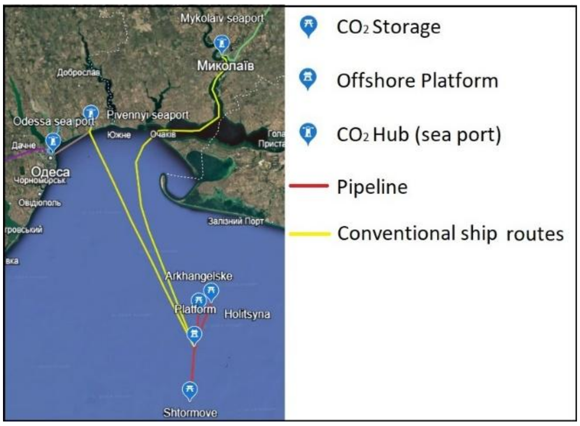

Figure 34. Scenario-2 – Conventional ship routes from Pivdennyi and Mykolaiv seaports to an offshore injection platform.

<u>Scenario-2. Conventional ship</u>

In Scenario II, two ships separately will transport CO_2 from the Pivdennyi and Mykolaiv hubs to the Platform (Figure 3434). Once the CO_2 ship reaches the Platform, the liquid CO_2 is offloaded, typically through insulated pipelines or hoses—the total proposed distance for the conventional shipping routes is estimated as **670 km** (Table *31*31).

Table 31. Transport distance by conventional ship from ports to Platform in the Black Sea within the Ukrainian scenario.

Number	Distance description	Pipeline proposed length, km
1	Pivdennyi seaport – Offshore Platform – Pivdennyi sea- port	267.2
2	Mykolaiv seaport – Offshore Platform – Mykolaiv sea-port	402.8
	Total	**670**

<u>Scenario-3. NEMO ship solution</u>

Scenario III involves transporting CO_2 by NEMO ship with direct injection from the ship. In this scenario, the ship will depart from the port (hub), reaching each storage site in the Black Sea consequentially to inject directly CO_2. This approach will be evaluated separately for the Odesa and Mykolaiv regions. The total route distance using the NEMO solution for both areas is approximately 820.9 km (Table 32).

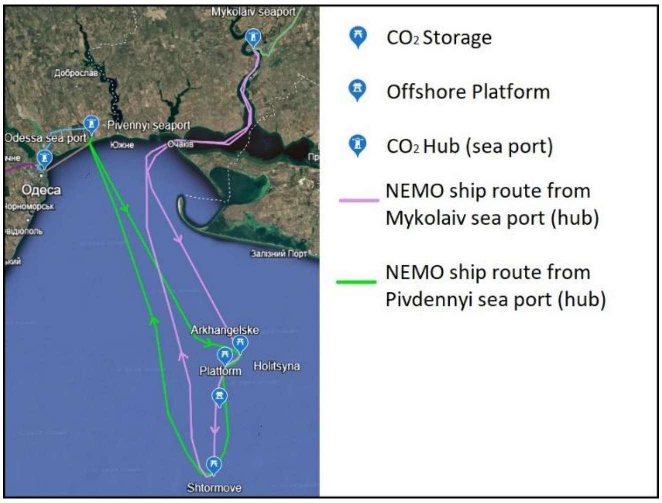

Figure 35. Scenario-3 – NEMO ship routes from Pivdennyi and Mykolaiv seaports.

Table 32. Transport distance by NEMO ship from ports to storage sites in the Black Sea within the Ukrainian scenario.

Number	Distance description	NEMO shipping length, km
1	Pivdennyi seaport – Holitsyna Storage	122
2	Holitsyna Storage – Arkhangelske Storage	9
3	Arkhangelske Storage – Shtormove Storage	48
4	Shtormove Storage – Pivdennyi seaport	163.5
	Total for Pivdennyi cluster	**342.5**
5	Mykolaiv sea port – Holitsyna Storage	182
6	Holitsyna Storage – Arkhangelske Storage	9
7	Arkhangelske Storage – Shtormove Storage	48
8	Shtormove Storage – Mykolaiv seaport	236.8
	Total for Mykolaiv cluster	**475.8**
	Total	**818.3**

6.2.5 Summary

The Ukrainian base case scenario is assessed at a regional scale. It includes Odesa and Mykolaiv clusters, both industrial and strategically located near the Black Sea, with total reported CO_2 emissions of 1.26 Mt CO_2 in 2023 (*Table 33*). Pivdennyi and Mykolaiv Sea ports were identified as strategic hubs for CO_2 emissions. Holitsyna, Arkhangelsk and Shtormove gas and gas condensate fields are considered potential CO_2 storage sites in Ukraine, with a total estimated CO_2 storage capacity of approximately 9.39 Mt (*Table* 2933). CO_2 emissions will be transported by (1) a pipeline system with an estimated total length of 294.6 km, (2) a conventional ship from ports to Platform with a total route distance of 670 km, and (3) a NEMO ship from ports to storage sites with a total route distance of about 820 km.

Table 33. Summary of Parameters for the Black Sea Scenario for Ukraine.

CO_2 emissions		**Ports**	**CO_2 Storage sites**		**Transport**			
CO_2 clusters	CO_2 emissions produced in 2023, Mt		Storage sites	Storage sites capacity, Mt	Onshore pipeline, km	Offshore pipeline, km	Conventional Ship, km	NEMO Ship, km
Odesa	0.72	Pivdennyi	Holitsyna	3.33				
Mykolaiv	0.54	Mykolaiv	Arkhangelske	1.95				
			Shtormove	4.11				
Total	**1.26**			**9.39**				
Total distance transport, Scenario-1, km					86.4	208.2		
Total distance transport, Scenario-2, km							670	
Total distance transport, Scenario-3, km								818.3
Total					**86.4**	**208.2**	**670**	**818.3**

These scenarios provide a basic framework and aim to foster synergy with the Romanian scenario to develop an integrated Black Sea scenario. This integration faces key risks, mainly related to the geological part, regulatory regimes, economic aspects and the unfavourable geopolitical framework (Table 34). Additional CO_2 emissions from neighbouring industrial regions could also be applied to the proposed hubs. However, further research is necessary to identify the most cost-effective and economically viable solution.

Table 34. Potential risks across the Black Sea scenario.

Risk	**Risk description**
Technical and regulatory	Lack of CCS regulations in Ukraine, experience and legal framework for offshore CO_2 storage in the Black Sea introduces challenges in ensuring compliance with international regulations and standards.
Geological reliability and availability	The integrity of subsurface reservoirs remains uncertain without detailed site-specific assessments. Variability in reservoir characteristics may impact injectivity and storage capacity, leading to inefficiencies. Long-term reliability could be affected by geochemical reactions or pressure build-up in reservoirs.

Risk	Risk description
	Availability of suitable geological formations for CO_2 storage may be constrained by competing uses, regulatory restrictions or limited geological data, restricted by confidential data of oil companies.
Data accuracy and availability	Incomplete or inconsistent subsurface data may lead to uncertainty of CO_2 storage capacity estimations. Geological interpretations may need frequent updates to models and storage estimates, increasing costs and complexity. Gaps in data availability will require additional exploration of storage sites.
Economic	High infrastructure costs, including pipelines, platforms, or specialised ships, may impact project budgets. Economic viability could be affected by inflation, supply chain disruptions, or unforeseen technical complications.
Geopolitical	Uncertainty in geopolitical stability in Ukraine poses challenges to planning and implementation timelines.

The Black Sea region offers significant potential for scaling up CCS initiatives. However, realising this potential requires addressing key challenges through comprehensive risk mitigation strategies, establishing robust regulatory frameworks and harmonising cross-border policies to ensure seamless collaboration among regional stakeholders. Equally critical is the development of targeted financial incentives to attract investment, foster innovation, and ensure the long-term viability of CCS projects.

7. Western Coast of Portugal

7.1 Introduction

The Western Coast of Portugal scenarios in the CTS project refer to the offshore storage of CO_2 emissions from Portugal stationary emitters and were defined having in consideration: i) the national decarbonisation policies; ii) CCUS scenarios and evaluations from previous studies; iii) emitters manifestation of interest in CCUS.

The key documents driving Portugal's national decarbonisation strategy include the **National Energy and Climate Plan (PNEC 2030)**[96], first introduced in 2019 and revised in 2024, which sets the strategic framework for carbon neutrality by 2050; the **Carbon Neutrality Roadmap 2050 (RNC 2050)**[97],

[96] https://files.diariodarepublica.pt/1s/2020/07/13300/0000200158.pdf : Accessed in August 2024

[97] https://www.portugal.gov.pt/download-ficheiros/ficheiro.aspx?v=%3d%3dBAAAAB%2bLCAAAAAAABACzMDexBAC4h9DRBAAAAA%3d%3d : Accessed in August 2024

established in 2019, that outlines the paths to achieve carbon neutrality by defining key guidelines and identifying the most cost-effective strategies; the **National Hydrogen Strategy (EN-H2)**[98] approved in 2020, that emphasises green hydrogen as an integral part of the energy transition and defines the strategy for its integration; and the **Portuguese Climate Law (DL98/2021)**[99], enacted in 2021, which provides the overarching legal structure for these initiatives.

The **PNEC 2030**, revised in 2024, sets more ambitious greenhouse gas (GHG) emissions reduction targets than the original plan. It now aims for a 55% reduction in GHG emissions by 2030 compared to 2005 levels (~75 Mt) and accelerates the goal of achieving carbon neutrality until 2045 instead of 2050. Other specific targets are: to reach 51% of energy consumption from renewable energy sources by 2030, to be achieved by a substantial increase in the solar and wind capacities; to increase energy efficiency by reducing primary energy consumption by 35%; to utilise green hydrogen as a mean to decarbonising high-heat industries and to store energy.

In the **RNC 2050** CCUS is not emphasised as a primary strategy for achieving carbon neutrality. Portugal's strong potential for higher integration of renewable energy sources anticipated high CCUS costs, and the relatively conservative projections for the future activity of the cement industry, one of the sectors where CCUS could be cost-effective, contributed to its constrained emphasis on the roadmap. This plan was shifted by the 2024 revision of **PNEC 2030**, where CCUS is mentioned as an essential technology to help Portugal meet its decarbonisation target in hard-to-abate industries where reducing emissions is challenging (e.g. Cement) and where other forms of decarbonisation might be more difficult or less effective. The plan also emphasises the need for innovation and investment in CCUS, pointing to the need for research and development to improve the efficiency and cost-effectiveness of these technologies and to plan the necessary infrastructure. Furthermore, CO_2 utilisation may be an option related to the production of low-carbon hydrogen and other sustainable fuels. Bioenergy with carbon capture and storage (BECCS) may also be relevant for the pulp & paper and waste sectors, which would lead to negative emissions.

The CTS scenarios are an evolution of the scenarios developed in the Strategy CCUS[100] project, which initially included 13 emitters from the **Cement**, **Pulp & Paper**, and **Glass** sectors located on the Western Coast of Portugal, between the cities of Setúbal and Figueira-da-Foz. Although the main sectors identified in previous studies as promising for CCUS in Portugal are Cement, Pulp & Paper and Glass, the CTS scenarios will also include the **Oil Refining**, **Chemicals**, and **Waste management** sectors.

Refining of mineral oil and chemical production sectors was included due to their very high CO_2 emissions and favourable geographical location in the Sines industrial cluster, close to the largest deep waters port in Portugal, the Sines port. Despite the unclear future of its medium- to long-term operations, the Sines refinery is also the largest current emitter in Portugal. Together, including these emitters represents ca. 3.25 Mt of CO_2 (2023 data) with potential for ship transport and direct injection. Waste management facilities, or more precisely, waste incinerating facilities, were included due to the potential to generate negative emissions from the part of emissions that can be regarded as biogenic. These facilities emitted around 0.86 Mt of biogenic and non-biogenic CO_2 in 2022.

The Portuguese scenarios target 24 emitters from the Cement, Pulp & Paper, Glass, Oil refining, Chemicals, and Waste sectors, 13 already evaluated in the Strategy CCUS project and 11 newly added to the analysis. From this set, 23 emitters are geographically located in a north-south axis between the

[98] https://www.dgeg.gov.pt/media/5eac1vcd/resolu%C3%A7%C3%A3o-do-conselho-de-ministros-n-%C2%BA-632020.pdf : Accessed in August 2024
[99] https://files.dre.pt/1s/2021/12/25300/0000500032.pdf : Accessed in August 2024
[100] https://strategyccus.brgm.fr/sites/default/files/LB/LB.html#8/39.684/-8.823

cities of Porto and Sines and represent the major stationary emitters in the country (excluding fossil fuel-based power plants because CCUS will not be necessary for the power-producing sector according to the current decarbonisation plans). Additionally, a cement factory located in the Algarve, around 120 Km from Sines, will also be considered. The storage site, characterised in the PilotSTRATEGY[101] project, is located offshore from the Figueira da Foz port, around 20 km from the coast. Four shipping routes will be analysed within the ship transport and direct injection scope of the CTS project. The need for flexibility imposed one during the initial stage of the implementation (pilot scenario/phase) of the PilotSTRATEGY project and three focused on the southern emitters from Lisbon, Setúbal and Sines.

7.2 CO_2 Emissions

The emissions of the 24 CO_2 sources were 14 Mt of CO_2/y (2022 and/or 2023 data), with ca. 6.2 Mt from biogenic origin and 7.9 Mt/y from fossil and process emissions (Table 35). The pulp and paper sector mainly drives biogenic emissions with 4.7 Mt of CO_2/y, energy from biomass contributes with 0.6 Mt/y, and waste management facilities are expected to represent up to 0.9 Mt/y. The cement sector has the highest emissions of CO_2, with 3.6 Mt of CO_2 and oil refining at 2.4 Mt. Together, these sectors represent around 75% of the total fossil-based and process emissions of the considered emitters.

The map in Figure 36 illustrates the geographical distribution of the emitters and their industrial sectors (further detailed in Table 35); they can be classified into 6 clusters: Porto, Figueira da Foz, Leiria, Lisbon, Setúbal, and Sines, with three additional isolated sources in Aveiro, Coimbra and Loulé.

[101] https://pilotstrategy.eu/

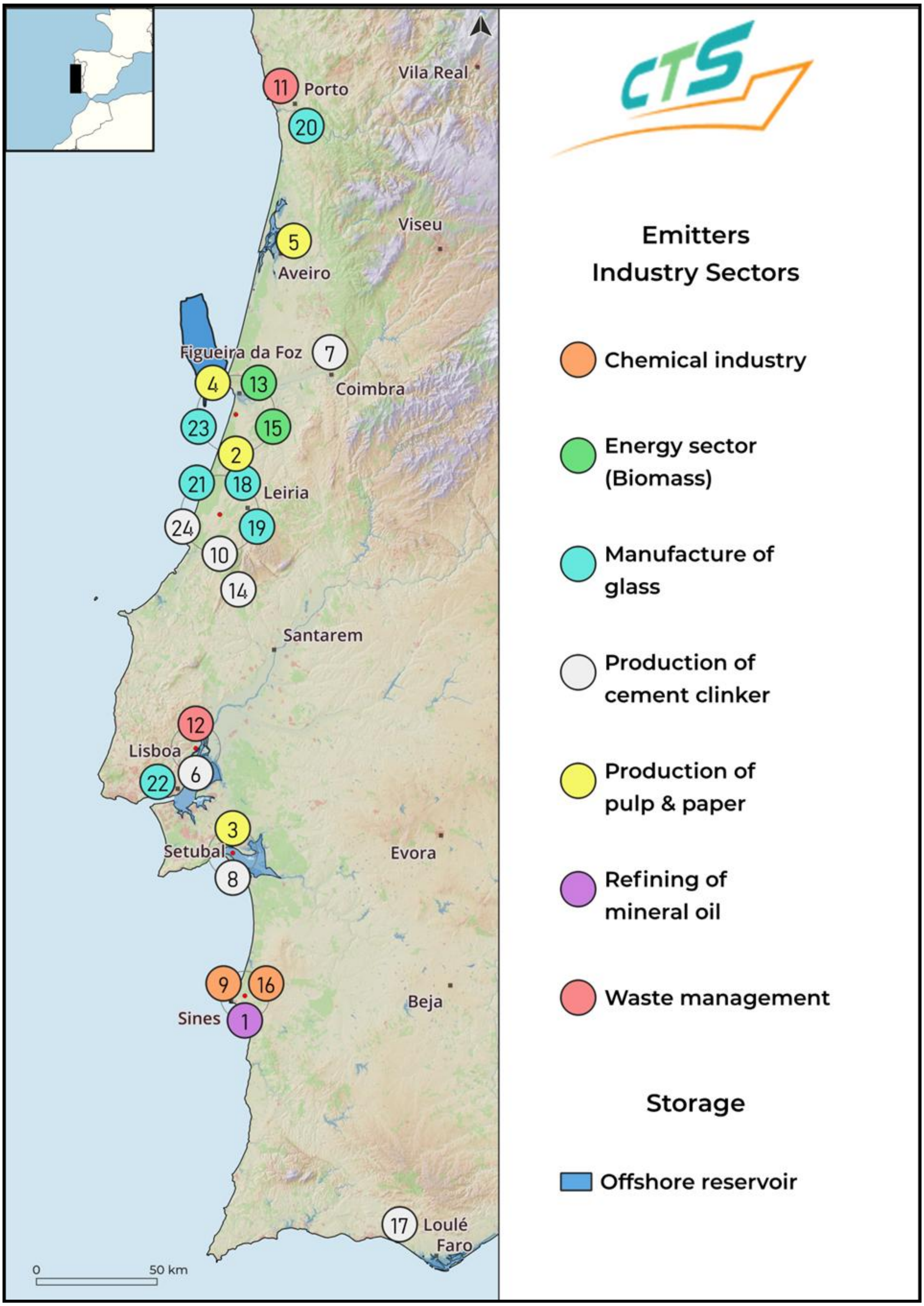

Figure 36. Western Coast of Portugal scenario, emitters distribution and industry sectors.

Table 35. List of emitters in the Portuguese scenario.

ID	EU ETS ID of the plant	Emitter Name	Region	Sector	Emissions Source	Emissions Year	Fossil CO_2, t/yr	Bio CO_2, t/yr	CO_2 emissions, t/yr
1	196	Petrogal	Sines	Refining of mineral oil	ETS	2023	2,359,568		2,359,568
2	291	Navigator Figueira	Figueira da Foz	Production of Pulp & Paper	Emitter	2023	117,000	1,613,000	1,730,000
3	277	Navigator Setubal	Setubal	Production of Pulp & Paper	Emitter	2023	273,000	1,136,000	1,409,000
4	48	CELBI Figueira	Figueira da Foz	Production of Pulp & Paper	EPRT (total) ETS (fossil)	2022	58,841	1,001,159	1,060,000
5	145	Navigator Cacia	Aveiro	Production of Pulp & Paper	Emitter	2023	67,000	972,000	1,039,000
6	173	CIMPOR Alhandra	Alhandra	Production of cement clinker	ETS	2023	897,204		897,204
7	174	CIMPOR Souselas	Souselas	Production of cement clinker	ETS	2023	841,708		841,708
8	102	SECIL Outão	Outão	Production of cement clinker	ETS	2023	825,003		825,003
9	42	Indorama PTA	Sines	Chemical industry	EPRT	2022	591,000		591,000
10	103	SECIL Maceira-Liz	Maceira	Production of cement clinker	ETS	2023	434,983		434,983
11	-	Lipor	Maia	Waste and management	EPRT**	2022		371,000	371,000
12	-	Valorsul	São João da Talha	Waste and management	EPRT**	2022		490,000	490,000
13	-	CTB Figueira A	Figueira da Foz	Energy sector	EPRT*	2022		340,000	340,000
14	79	Lhoist	Alcanede	Production of cement clinker	ETS	2023	310,681		310,681
15	-	CTB Figueira B	Figueira da Foz	Energy sector	EPRT*	2022		302,000	302,000
16	252	Repsol	Sines	Chemical industry	ETS	2023	256,795		256,795
17	202	CIMPOR Loulé	Loulé	Production of cement clinker	ETS	2023	233,746		233,746
18	52	Gallo Vidro	Marinha Grande	Manufacture of glass	ETS	2023	106,555		106,555
19	49	Santos Barosa	Lisboa	Manufacture of glass	ETS	2023	105,894		105,894

ID	EU ETS ID of the plant	Emitter Name	Region	Sector	Emissions Source	Emissions Year	Fossil CO_2, t/yr	Bio CO_2, t/yr	CO_2 emissions, t/yr
20	99	BA Glass Avintes	Avintes	Manufacture of glass	ETS	2023	105,866		105,866
21	98	BA Glass Marinha Grande	Marinha Grande	Manufacture of glass	ETS	2023	90,097		90,097
22	177	BA Glass Lisboa	Lisboa	Manufacture of glass	ETS	2023	86,055		86,055
23	104	SECIL Pataias	Pataias	Production of cement clinker	ETS	2023	72,336		72,336
24	45	Verallia Portugal	Figueira da Foz	Manufacture of glass	ETS	2023	66,008		66,008
						Total	**7,899,340**	**6,225,159**	**14,124,499**

* Biogenic emissions were assumed; they may be lower.
** Only a percentage of the emissions from waste management are biogenic. They are listed here as biogenic for simplification and in the absence of detailed information.

7.3 CO_2 Storage Site

The initial storage site is located in the Northern sector of the Lusitanian Basin, approximately 20 km offshore from Figueira da Foz (Figure 37). The identification and selection of this storage site, a geological structure defined as a smooth anticline shape, designated as Q4-TV1, resulted from the subsurface geo-characterization studies[102] conducted within the scope of the PilotSTRATEGY project. In these studies, petroleum legacy well data and 2D/3D seismic reflection data were utilised for the petrophysical and geophysical interpretation of the storage complex elements in the offshore setting of the basin and to define the reservoir and caprock depositional and conceptual geological models of this area.

The geological framework (Figure 38) of the offshore setting of the Lusitanian basin[102,103] is characterised by the siliciclastic deposits of the Torres Vedras Group (Early Cretaceous), which serves as a potential reservoir to store CO_2. This reservoir is capped by the carbonates/ marls of the Cacém Formation (Late Cretaceous), acting as the seal. Above this lie the siliciclastic deposits of the Aveiro Group (Late Cretaceous), which may function as a potential seal, with additional overburden layers composed of Paleocene and Eocene-Miocene dolomites and siliciclastic deposits, respectively. The reservoir underburden comprises Upper Jurassic siliciclastic deposits and carbonates, as well as carbonates of the Middle Jurassic.

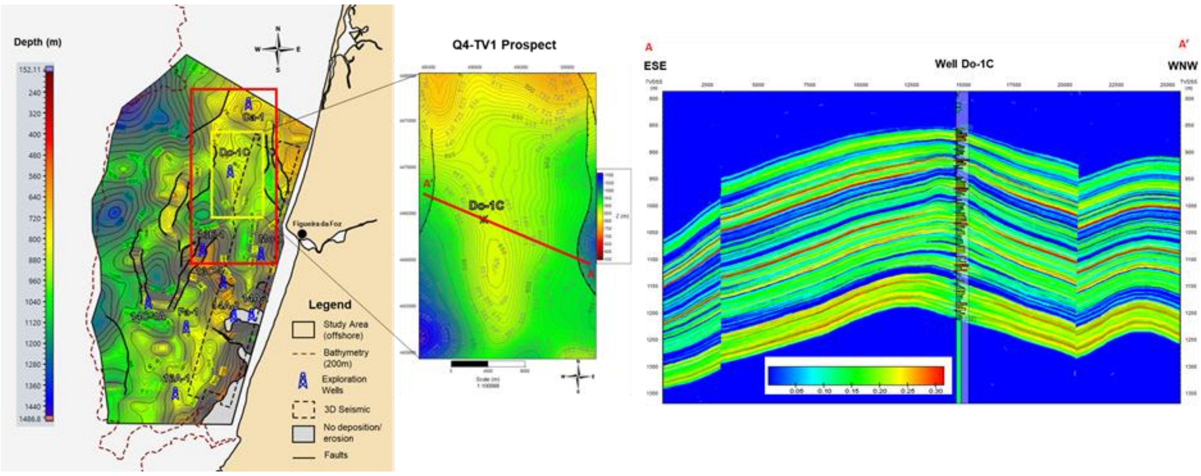

Figure 37. Map of the top of the Torres Vedras Group reservoir structure illustrating the outlines of the study area of the 3D static model's boundary (red rectangle) and the reservoir model boundary covering the area of the Q4-TV1 prospect (yellow rectangle).

[102] [Marques da Silva, D., Caeiro, M. H., Pereira, P., Ribeiro, C., Carneiro, J., Casacão, J. & Pina, B. (2023). Lusitanian Basin (Portugal). In Wilkinson, M. (Ed.), Report on Conceptual Geological Models. Deliverable WP2/D2.7, EU H2020 PilotSTRATEGY project 101022664 report.]

[103] Pereira, P., Ribeiro, C., & Carneiro, J. (2021). Identification and characterisation of geological formations with CO_2 storage potential in Portugal. Petroleum Geoscience, 27(3), Thematic Collection: Geoscience for CO_2. https://www.earthdoc.org/content/journals/10.1144/petgeo2020-123.

Table 36. Reservoir parameters for the CO_2 storage site at structure Q4-TV1.

Parameters Q4-TV1	Value	Unit
Depth of reservoir top [a]	820–1178	m
Reservoir Net-Porous Volume[b]	658–727/709	m^3 ($x10^7$)
CO_2 density	580	kg/m^3
Salinity	56	g/L
Permeability[c]	5–1541/122	mD ($10^{-6}m^2$)
Porosity[c]	8–32/11	%
Temperature	42	°C
Storage efficiency factor[b]	10–3.1/6.1	%
Optimistic CO_2 storage capacity	421	Mt
Conservative CO_2 storage capacity	123	Mt
Most Likely CO_2 storage capacity	251	Mt

[a] (min-max); [b] (Optimistic-Conservative/ Most Likely); [c] (min-max/avg)

The storage capacity values presented resulted from the net-porous volumes (conservative, most likely and optimistic values) of the reservoir conducted in the static model building with uncertainties[104], based on a set of 300 stochastic simulations of the static model. In this approach, the spatial distribution and continuity patterns of the reservoir effective porosity (Figure 38**Error! Reference source not found.**) and net-to-gross, as well as spatial variations of the reservoir thickness, were considered for this area, including the Q4-TV1 storage site.

Although this storage site and the surrounding area may have enough capacity to store all the CO_2 anticipated in the CTS scenarios, due to the expected large CO_2 volumes to be stored and to account for storage integrity and safety purposes, the selection of Q4-TV1 as the initial site took into account the possibility to upscale the CO_2 storage to other structures in the same reservoir of this sedimentary basin and located at around the same distance from the coast. Since the characterisation of those structures/sites is beyond the scope of CTS (and even in PilotSTRATEGY), it will be assumed that the costs imposed to store in any such structure will be similar to those of the Q4-TV1 storage site.

After completing a detailed 3D static geological model with uncertainties[105], spanning approximately 1925 km² of the offshore setting (Figure 37), subsequent studies of dynamic simulations have been conducted in the PilotSTRATETGY project to define the optimal location for an injection well[106].

[104] Pereira, P., Caeiro, M.H., Carneiro, J., Khudhur, K., Ribeiro, C., Lopes, A.M., Santos, M. & Marques da Silva, D. (2024). Lusitanian Basin (Portugal). In Bouquet, S. (Ed.), Report on static modelling with uncertainties. Deliverable WP3/D3.2, EU H2020 PilotSTRATEGY project 101022664 report, 105-139.
[105] Pereira, P., Caeiro, M.H., Carneiro, J., Khudhur, K., Ribeiro, C., Lopes, A.M., Santos, M. & Marques da Silva, D. (2024). Lusitanian Basin (Portugal). In Bouquet, S. (Ed.), Report on static modelling with uncertainties. Deliverable WP3/D3.2, EU H2020 PilotSTRATEGY project 101022664 report, 105-139.
[106] Khudur, K., Pereira, P., Carneiro, J., Hardwick, J., Santos, M. & Casacão, J. (2024). Lusitanian Basin (Portugal). In Chassagne, R. (Ed.), Report on storage capacity optimization. Deliverable WP3/D3.3, EU H2020 PilotSTRATEGY project 101022664.

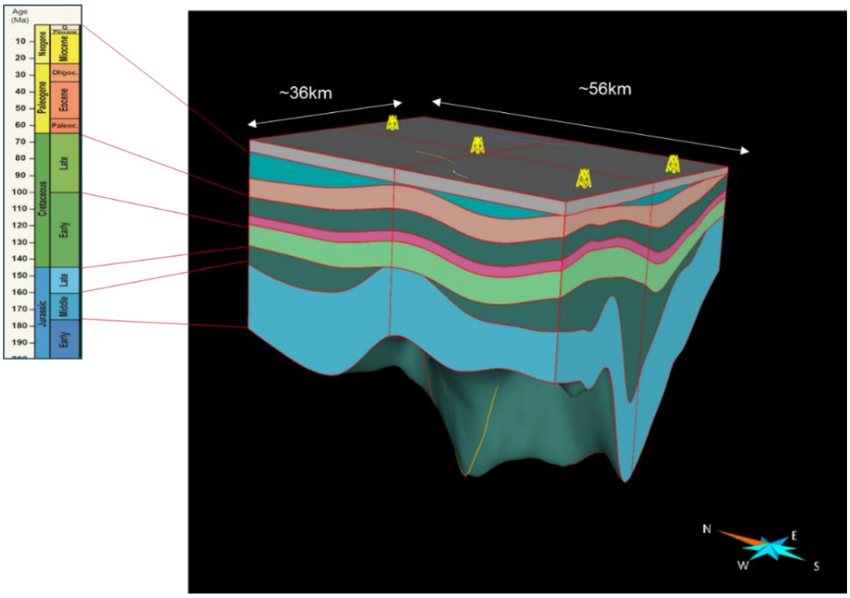

Figure 38. The static model built in the PilotSTRATEGY project shows the different geological units, including the reservoir Torres Vedras Group (Early Cretaceous) and the caprock Cacém Formation (Late Cretaceous).

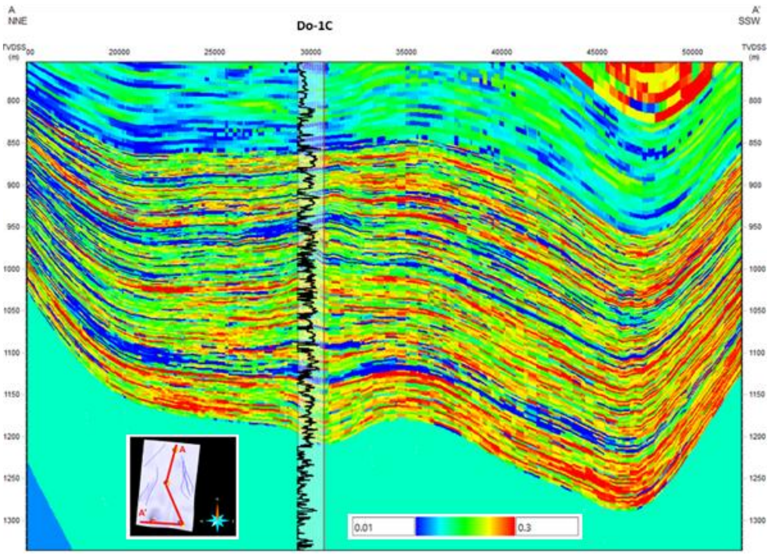

Figure 39. One realisation of the stochastic simulation of effective porosity is shown in a cross-section of the static model for the reservoir region at the structure of the Q4-TV1 prospect.

The well location and permissible injection rate were selected to ensure that the pressure buildup remains below thresholds that could induce fracturing of the reservoir rock. Additionally, these parameters were optimised to prevent the CO_2 plume from reaching the closest legacy oil exploration well (Do-1C) abandoned in 1975 and the fault systems located to the east and west of the Q4-TV1 structure (Figure 40). The injection rate varies between 0.5 Mt/y and 0.7 Mt/y over a 30-year injection period, with the perforation interval for injection occurring at depths ranging from 1180 meters to 1230 meters below sea level.

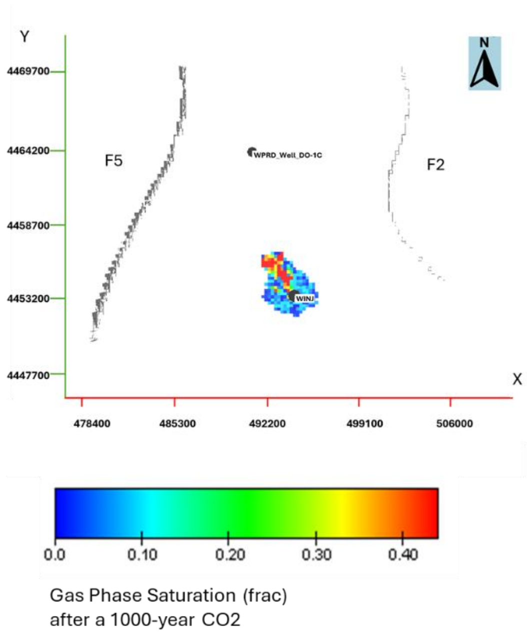

Figure 40. Gas phase saturation up to 1000 years of the CO_2 plume evolution. An effective containment of the CO_2 plume is verified as it remains away from the legacy well Do-1C and the existing faults (F5 and F2).

The ongoing studies of the PilotSTRATEGY project focus on the storage site at Q4-TV1 in terms of reservoir performance, simulating the interactions and trapping mechanisms of the CO2 plume dispersion over the long-term injection and post-injection timeframe. In addition, the reservoir containment is also currently being addressed in the simulation studies, particularly the potential risks associated with the storage site integrity, by conducting geochemical and geomechanical assessments, as well as evaluating the potential for reactivation of the faults surrounding the storage site (Figure 40).

7.4 CO_2 Transport

In the scope of CTS, four long-term transport scenarios and a pilot phase scenario will be analysed. The pilot phase, linked to the PilotSTRATEGY project, only considers train and ship CO_2 transport. These options are not expected to be economically viable, and they aim to test the reservoir and capture technologies without deploying permanent or hard-to-shift facilities and equipment. Figure 41 illustrates the pilot scenario, with two capture pilots being implemented in a cement factory in Souselas and a glass factory in Marinha Grande to capture 60 kt and 30 kt of CO_2 per year, respectively. The transport from each facility to the Figueira da Foz port would be conducted by train, around 8 kt of CO_2 per trip, and by ship from the port to the offshore reservoir site for direct injection of 90 kt of CO_2 per year, totalling 270 kt during three years. The Figueira da Foz port has some constraints for receiving large ships. In the short term, these constraints must be considered when assessing the possibility of renting or testing ships equipped for direct injection.

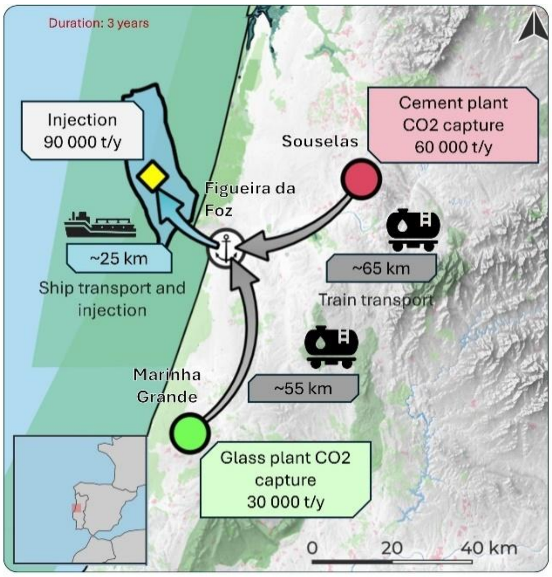

Figure 41. Schematics of the pilot scenario.

The long-term scenarios will test the transport exclusively by pipeline and the transport and injection directly from a ship for the Sines, Setúbal and Lisbon clusters (**Error! Reference source not found.**).

For the pipeline transport, around 700 km of new dedicated CO_2 pipelines are expected to connect all CO_2 emitters. The spatial distribution of the emitters and the existing natural gas pipeline network have a strong synergy and could allow CO_2 pipelines to be built in the existing pipeline corridors. The natural gas pipeline operator, REN, would also be a strong candidate for operating the CO_2 pipeline network.

In relation to ship transport, the Sines cluster is composed of three emitters, totalling 3.25 Mt of CO_2 per year, located in the vicinity of the port—the distance to the injection point represents a shipping route of around 320 km. The Port of Sines is an open deep-water seaport with excellent maritime access and leads the national port sector in the volume of cargo handled. It has no restrictions on receiving any type of ship and currently hosts modern specialized terminals that are able to handle different kinds of cargo.

Setúbal cluster has two emitters, aggregating 2.2 Mt of CO_2 per year; besides both facilities having dedicated docking ports, they are also at distances up to 6 km from the Port of Setúbal. This port is located on the Sado River estuary, with natural maritime access and protection conditions. The ship route to the injection site would be around 300 km.

Lisbon cluster has three emitters with a total of 1.4 Mt of CO_2 emissions per year. Two of them are located near the Tagus river north bank. The farthest emitter from the Lisbon port area is a cement plant, located at around 30 km, which is also the largest of the three in terms of CO_2 emissions, with 0.9 Mt of CO_2 per year. The Port of Lisbon could be a solution for ship transport. It is considered an important link between the Mediterranean and Northern Europe, with Port activities being carried out on both banks of the Tagus river. Still, liquid cargo is only handled on the south bank, which may be disadvantageous because the emitters are located on the other bank. The ship route from the Lisbon port to the injection site would be around 230 km.

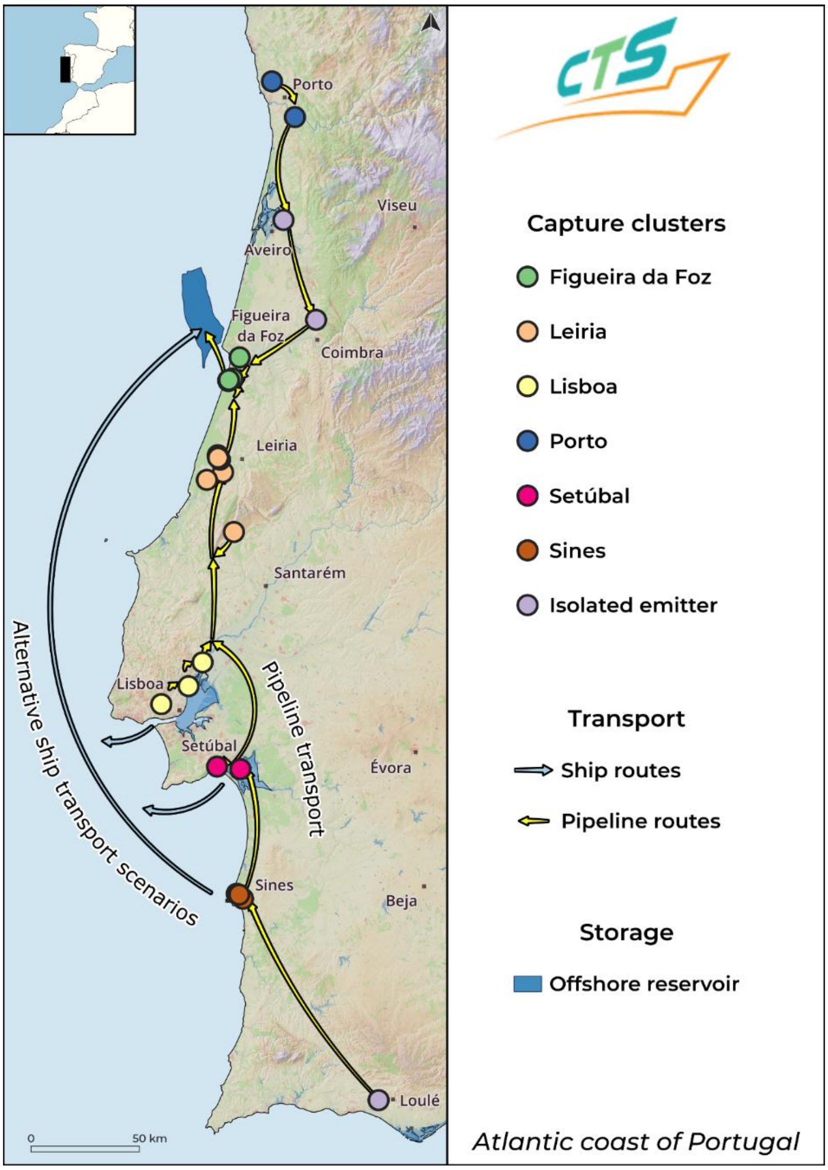

Figure 42. Clusters, schematic pipeline network and alternative ship transport routes for the Western coast of Portugal scenarios.

Table 37. Clusters, emissions and ship route distances to offshore storage.

Cluster	Emitter ID	Plant Name	Total CO_2 (t/yr)	Pipeline Network (km)	Ship distance to storage (km)
Sines (Sines Port)	1	Petrogal	2,359,568	8	320
	9	Indorama PTA	591,000		
	16	Repsol	256,795		
		Total	**3,207,363**		
Setubal (Setúbal Port)	3	Navigator Setúbal	1,409,000	12	300
	8	SECIL Outão	825,003		
		Total	**2,234,003**		
Lisboa (Lisboa Port)	6	CIMPOR Alhandra	897,204	35	230
	12	Valorsul	371,000		
	22	BA Glass Lisboa	86,055		
		Total	**1,354,259**		
Leiria (Pipeline transport to storage)	10	SECIL Maceira-Liz	434,983	100	
	14	Lhoist	310,681		
	18	Galo Vidro	106,555		
	19	Santos Barosa	105,894		
	21	BA Glass Marinha Grande	105,894		
	23	SECIL Pataias	72,336		
		Total	**1,120,546**		
Figueira da Foz (Pipeline transport to storage)	2	Navigator Figueira	1,730,000	40	
	4	CELBI Figueira	1,060,000		
	13	CTB Figueira A	340,000		
	15	CTB Figueira B	302,000		
	24	Verallia Portugal	66,008		
		Total	**3,498,008**		
Porto (Pipeline transport to storage)	20	BA Glass Avintes	105,866	120	
	11	Lipor	371,000		
		Total	**476,866**		
Isolated sources	5	Navigator Cacia	1,039,000	50	
	7	CIMPOR Souselas	841,708	50	~25 (pilot phase)
	17	CIMPOR Loulé	233,746	~150 km to Sines port	
		Total	**2,114,454**	**565**	

7.5 CO_2 Use

Some CO_2 may be allocated to produce synthetic fuels; this assessment will consider the relevant national policies and regulations (e.g., the National Hydrogen Strategy).

7.6 Summary

The Atlantic coast of Portugal is considered to have 24 emitters, mainly along the country's western coast (Figure 36). Together, these emitters produce around 14 Mt of CO_2 annually (2022 and 2023 data) (see Table 38). The scenarios will consider capturing around 60% of these emissions (8.3 CO_2 Mt/y) and injecting them in an offshore reservoir at around 20 km of Figueira-da-Foz (Figure 36). Biogenic emissions will be considered for storage, generating negative emissions, but part of them may be diverted to the production of synthetic fuels.

Large-scale, long-term ship transport will be considered for three clusters (Sines, Setúbal, Lisboa), where transporting around 4 Mt of CO_2 per year will be evaluated. These clusters are near shore, and the transport to the port is expected to be performed by a total of ~55 Km of pipelines. The remaining clusters (Leiria, Figueira-da-Foz, Porto) and the isolated emitters in Cacia and Souselas will have transport exclusively by pipeline (~360 km), with the offshore portion (~25 km) departing from the surroundings of Figueira-da-Foz port. The Loulé cement plant, the most remote of them all, will connect to Sines port by pipeline (~150 km).

Table 38. CO_2 emissions are produced, captured, used and transported on the Atlantic coast of Portugal Scenario [107].

Cluster	Number of plants	CO_2 produced, Mt/y	CO_2 captured, Mt/y	CO_2 used, Mt/y	CO_2 transported, Mt/y	Ship distance from port to storage site, km
Sines	3	3.21	1.92		1.92	320
Setúbal	2	2.23	1.23		1.23	300
Lisboa	3	1.47	0.88		0.88	230
Leiria	6	1.12	0.81		0.81	
Figueira-da-foz	5	3.50	1.17		1.17	25
Porto	2	0.48	0.41		0.41	
Isolated	3	2.11	1.85		1.85	
Total	**24**	**14.12**	**8.28**		**8.28**	**875**

The capture profile for the 11 new emitters considered for the CTS scenarios was adapted from the methodology developed for scenario design in the StrategyCCUS project[108]. It considers the national decarbonisation plans and industry sectors that may be relevant for CCUS if industries will not deploy capture simultaneously and some will have other decarbonisation measures. Therefore, the available CO_2 amount for capture is not expected to be equivalent to present emissions. The original 13 emitters from Strategy CCUS kept the same capture profile. Since the Sines cluster emitters and respective sectors were not evaluated before, an empirical value of 60% of the current emissions was considered at this time; this value is based on the expectancy that at least the refinery will decrease emissions in the future in time.

[107] Values for a 15-year average (2035-2050), if capture in a given facility starts after 2035, maintaining the same capture rate, the total CO_2 values may decrease and yearly values may increase.
[108] https://strategyccus.brgm.fr/sites/default/files/D5.2_CCUS_BusinessCases.pdf

8. Comparison of Scenarios

The presented scenarios in four CTS sea regions include 12 countries (Norway, 10 EU countries and Ukraine) and storage sites in six countries.

The North Sea scenario is the largest in all of the CCS value chain and will significantly reduce emissions. It includes 7 CO_2 emission clusters in Denmark and Norway with 30 emitters that captured about 13.6 Mt/y CO_2 transported from seven ports and stored in the number of storage sites in Denmark and storage locations in Norway and about 40–63 Mt/y CO_2 transported from four North Sea European ports in Germany, France, Belgium and The Netherlands. About 54–76 Mt/y CO_2 will be transported and stored under the North Sea in the storage formations, including DOF and DSA in Denmark and DSA in Norway.

The Baltic Sea scenario includes three Baltic States (Estonia, Latvia and Lithuania) with 4 clusters, 16 emitters and one storage site in DSA offshore Latvia. More than 8 Mt CO_2 will be transported from four ports in three countries and stored annually in the E6 structure in Latvia, while 0.9 Mt CO_2 can be used. The CO_2 mineral carbonation project from Estonia developed and patented by TalTech and Ragn-Sells, is included in the Baltic Scenario, with possible future considerations for the increase in bio-CO_2 and CO_2 use in all three Baltic states. CO_2 use case for CO_2 mineral carbonation with oil shale ash (BOS) for production of PCC will utilise about 0.25 Mt/y CO_2 and 1.3 Mt/y of OSA to produce 0.5 Mt/y PCC.

Table 39. Comparison of scenarios in four Sea Regions.

CTS Scenario and countries	Clusters and EU hubs	Emitters in clusters	CO_2 produced 2023 Mt/y	CO_2 captured Mt/y	CO_2 trans-ported Mt/y	Offshore storage sites /DSA/DGS /DOF*	Average storage capacity, (conser-vative - opti-mistic) Mt	Pipelines/other transport - distance to ports km	Ports	Ship distance from port to storage site km
North Sea										
Denmark	West	2	1.57	1.5	1.5	Inez	178	4	Esbjerg	200
	Center	9	5.51	5.2	5.2	Jammerbugt/Lisa	>200	35	Kalundborg	700
	East	3	0.83	0.8	0.8			60	Copenhagen	600
Total	3	14	7.92	7.5	7.5		>278		3	**1500**
Norway	North	3	2.23	2.1	2.1	Johansen and Cook	150	0	Mongstad	350
	Center	2	0.37	0.35	0.35	Hugin	50	0	Husnes	300
	South	4	1.41	1.3	1.3			0	Kårstø	350
	East	7	2.44	2.3	2.3	Gassum-	600	5	Herøya	460
Total	4	16	6.44	6.05	6.05		800		4	**1460**
Total in Denmark and Norway	**7**	**30**	**14.36**	**13.55**	**13.55**		**>1000**	**104**	**7**	**2960**
Wilhelmshavn, Germany				10	10	Bryne, Fiskebank, Gassum	1300–2800	0	Wilhelmshavn	450
Dunkerque (Dunkirk), France				1.5	1.5	Utsira, Sognefjord	2000–5500	0	Dunkerque	800

CTS Scenario and countries	Clusters and EU hubs	Emitters in clusters	CO_2 produced 2023 Mt/y	CO_2 captured Mt/y	CO_2 trans-ported Mt/y	Offshore storage sites /DSA/DGS /DOF*	Average storage capacity, (conser-vative - opti-mistic) Mt	Pipelines/other transport - distance to ports km	Ports	Ship distance from port to storage site km
Zeebruge, Belgium				20–40	20–40	Utsira, Sognefjord	2000–5500	0	Zeebruge	760
Emshaven, The Netherlands				9–11	9–11	Bryne, Fiskebank, Gassum	1300–2800	0	Emshaven	475
Total for North Sea Europe	4 hubs			40–62.5	40–62.5				4	2485
Total for the North Sea	**11 clusters and hubs**			**54–76**	**54–76**			**104**	**11**	**5445**
Baltic Sea										
Estonia	2	5	3.5	3.3	2.3	E6-A/DSA	146–365	104.4	Sillamäe	751
		3	0.43	0.41	6.05			46	Muuga	575
Latvia	1	2	0.7	0.67	13.55			22.6	Riga	402
Latvia-Lithuania	1/4	6	4.8	4.56	4.1			577.37	Klaipeda	90.5
Total	**4**	**16**	**9.43**	**8.94**	**8.06**	**1**	**146–365**	**750.37**	**4**	**1818.5**
Black Sea										
Romania	Călărași	2	0.15	0.14	0.14	Tomis/DSA	33	157.38	Midia	75
	Constanța	5	2.03	1.93	1.93	Tomis-Lebăda Est/DOF	33/25	80.1		72/75
Total	**2**	**7**	**2.18**	**2.07**	**2.07**	**2**	**58**	237.48	**1**	**144.2**
Ukraine	Odesa	NA	0.72	**0.68**	**0.68**	Holitsyna /DGF	3.33		Pivdennyi	342.5
	Mykolaiv	NA	0.54	**0.51**	**0.51**	Arkhangelske /DGF	1.95		Mykolaiv	475.8
						Shtormove /DGF	4.11			
Total	**2**	**NA**	**1.26**	**1.20**	**1.20**	**3**	**9.39**	**NA**	**2**	**818.3**
Total for the Black Sea	**4**		**3.44**	**3.27**	**3.27**	**5**	**67.39**	**474.96**	**3**	**962.5**
Western Coast of Portugal										
Portugal										
	Sines	3	3.21	1.92	1.92	Q4-TV1 /DSA	20–50 (for Pilot STRATE	8	Sines	320
	Setúbal	2	2.23	1.23	1.23			12	Setúbal	300

CTS Scenario and countries	Clusters and EU hubs	Emitters in clusters	CO_2 produced 2023 Mt/y	CO_2 captured Mt/y	CO_2 trans-ported Mt/y	Offshore storage sites /DSA/DGS /DOF*	Average storage capacity, (conser-vative - opti-mistic) Mt	Pipelines/other transport - distance to ports km	Ports	Ship distance from port to storage site km
	Lisboa	3	1.47	0.88	0.88		GY Q4-TV1 structure.)	35	Lisboa	230
	Leiria	6	1.12	0.81	0.81			100	Figueira-da-Foz	25
	Figueira-da-Foz	5	3.5	1.17	1.17			40		
	Porto	2	0.48	0.41	0.41			120		
	Isolated	3	2.11	1.85	1.85			250		
Total for Portugal	**6 + 3 isolated**	**24**	**14.12**	**8.28**	**8.28**	**1**	**98–293** for the northern sector of the Lusitanian basin	**565**	**4**	**875**
Total for CTS project	**26**				**74 - 96**			**1420**	**22**	**9101**

*DSA – Deep saline aquifer, DGF – depleted gas field, DOF – depleted oil field.

The Black Sea Scenario consists of Romanian and Ukraine scenarios, including transported in Romania 2.1 Mt/y CO_2 and in Ukraine 1.2 Mt/y CO_2. In Romania, captured CO_2 will be transported to one DSA and one DOF from one port located 75 km from DSA, while in Ukraine, three DGF will be used for storage of CO_2 transported from two ports in the Black Sea with a total distance from ports of about 820 km.

The Western Coast of Portugal scenario will target 8.3 Mt CO_2 from 24 industrial plants aggregated in six main clusters. Ship transport and injection will be considered for 4 Mt CO_2 from three southern ports to the offshore DSA reservoir. The total distance from ports is 875 km.

The Romanian part of the Black Sea scenario has the shortest total ship transport distance from the port to the storage site among all the proposed scenarios. However, in Portugal, the Figueira-da-Foz port is located around 25 km from the injection site; ship transport from this port was considered of possible relevance only in the pilot phase. The ship distance for the three ports to be considered for the long-term scenario ranges from 230 to 300 km. The Ukraine ports are located 343–476 km from the ports.

In the Baltic scenario, the Klaipeda port is located 91 km from the E6 storage site in Latvia, while Riga and Estonian ports are more distant (400–750 km).

In the North Sea scenario, the shipping distance from Danish ports is 200–700 km, from Norwegian ports are 300–460 km and from European ports in four countries are 450–800 km. The total distance for all the North Sea scenarios is the highest (about 5445 km).

The overall key parameters of the CCS scenario are the lowest in the Black Sea scenario and the highest in the North Sea.

Baltic and Western coasts of Portugal scenarios have a similar potential impact on CO_2 emissions reduction (8.3–8.9 Mt/y CO_2 captured). At the same time, the total distance from ports is lower in Portugal (875 km) versus 1819 km in the Baltic scenario. The total distance in the Black Sea scenarios (Romania and Ukraine) is 963 km, higher than in Portugal, but emission reduction is lower (3.3 Mt/y CO_2).

The storage capacity is also the highest in the North Sea scenario, as it includes several storage sites and storage locations (storage formations) in Denmark and Norway's North Sea national waters. The total capacity for this scenario is more than 1 Gt for Danish and Norwegian clusters but includes only the theoretical storage capacity in Norway for European CO_2 emissions transported from 4 ports. The practical storage capacity assigned to the 11 licenced areas in Norway is not available in the public sources.

Other scenarios include one storage site in one country (Baltic and Western Coast of Portugal scenarios) or small DSA, DOFs and DGF in one country (Romania and Ukraine). The total storage capacity in the Black Sea scenario is only 67 Mt. In Portugal, the effective storage capacity around the Q4-TV1 structure selected for PilotSTRATEGY ranges from 98 Mt (P10) to 516 Mt (P90), with a most likely value of 293 Mt for the northern sector of the Lusitanian basin being considered for CTS. After completion of the Q4-TV1 structure, other nearby structures will have to be utilised. In the Baltic scenario, the storage capacity of the E6 structure (conservative - optimistic) is in the same range as in Portugal (146–365 Mt).

Comparing the regulatory background permitting CO_2 storage under the seabed in the national waters and the export of CO_2 for offshore storage under the seabed, the situation is also not uniform in the four studied regions.

Denmark and Norway have implemented all the necessary national, regional, and international regulations in the North Sea scenario. Export of European CO_2 to Danish and Norwegian storage sites could be based on the OSPAR convention, as among the four involved EU countries, only The Netherlands implemented all needed regulations/amendments of the London Protocol.

The regulatory background on the Western Coast of Portugal is positive, and it is supported by national and regional CCS regulations (OSPAR). Still, an Allocation Plan must be approved in the National Maritime Spatial Planning framework, defining areas for offshore CO_2 storage before any CO_2 storage activities.

The regulatory situation is not yet evident in the Black Sea, where CCS regulations are unavailable in Ukraine and the Black Sea Convention.

The negative regulatory background is a challenge for the Baltic Sea scenario, as industrial-scale CO_2 storage is banned now in Latvia by national regulations and in the Baltic Sea by the HELCOM.

9. Conclusions

- Technical arrangement of CTS CCS/CCUS scenarios in four sea regions in different parts of Europe, in total, including 74–96 Mt/y CO_2 transported to and from 22 ports with shipping distances of more than 9 thousand km, are prepared for further techno-economic modelling in the WP3 of CTS project.

- The most extensive and complicated scenario is proposed for the North Sea, including captured CO_2 emissions and CO_2 hubs/ports in 6 countries and more than 10 storage sites and locations in two countries (Denmark and Norway).
- Romanian and Ukraine Black Sea scenarios are the smallest, including only 2.1 and 1.2 Mt/y of CO_2 emissions captured and transported to relatively small 2 and 3 storage sites, mainly depleted hydrocarbon fields and one DSA in Romania.
- The Baltic Sea International scenario applies only one storage site but 16 CO_2 emitters from Estonia, Latvia and Lithuania, located at different distances from 4 ports.
- The Western Coast of Portugal scenario plans to start injection at the PilotSTRATEGY chosen structure, Q4-TV1, likely to accommodate most of the local needs for storage, but the northern sector of the Lusitanian basin can resort to other nearby structures should that be required, as the 24 CO_2 emitters, located at different distances from 4 ports start capturing significant amounts of CO_2.
- The Baltic Sea scenario includes only one real CO_2 use case of CO_2 mineral carbonation with Estonian oil shale ash (BOS) and PCC production, with plans to involve bio-CO_2 in the CCU and extend CO_2 use products after 2040.
- The North Sea has needed regional and national regulations for offshore storage. At the same time, the Western Coast of Portugal scenario requires an Allocation plan to its Maritime Spatial Planning to be approved before initiating activities.
- The Baltic and Black Sea scenarios are more challenging because CO_2 storage regulations are not permitted in Latvia or the Baltic and Black Sea regions, and CCS regulations are unavailable in Ukraine.
- Baltic and Black Sea regions need changes in national and regional regulations, including a rising ban on CO_2 storage in Latvia, implementation of CCS regulations in Ukraine and development and implementation of CCS regulations by Helsinki and Black Sea Conventions.