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A framework for selection of promising CCUS value chains in the Baltic and Mediterranean regions: CCUS ZEN project study

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Abstract

This study proposes a framework for the initial screening of the most promising national and cross-border CCUS value chains at their very early stage of development. It applies to eight case studies from the Baltic and Mediterranean Sea regions conducted by the Horizon Europe CCUS-ZEN project. Technical and non-technical data were first collected and integrated into a common GIS project for eight countries in the Baltic Sea Region and five in the Mediterranean Sea Region. Internal and external groups of parameters were first developed to apply a SWOT analysis to the prospective CCUS cluster projects. Internal technical groups (strengths and weaknesses) include (1) CO_2 emission plants, (2) CO_2 storage sites, (3) available and planned infrastructure, and (4) CO_2 use options. An external technical group includes (1) characteristics of the area around the storage site, and non-technical external groups include (1) social, (2) political development, (3) international and national regulations, (4) MRV (Monitoring Reporting and Verification), (5) financial, (6) Readiness of CCUS value chain, which were analysed for opportunities and risks. The developed framework includes 24 internal quantitative technical parameters and 14 external qualitative parameters collected for eight CCUS value chains. For the qualitative parameters, an equivalent quantitative scaling method was designed to include external parameters in the quantitative SWOT analysis for the qualitative parameters. However, the export of CO_2 to offshore storage sites needs CO_2 storage regulations to be implemented internationally (London Protocol Amendment to article 6) and regionally (Helsinki and Barcelona Conventions), in addition to national regulations and permits needed for CO_2 storage both in onshore and offshore sites. Despite these differences,

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it is possible to perform a unified quantitative analysis for all projects (both onshore and offshore) by utilising common internal technical factors and a shortlist of external technical and non-technical parameters. Here, we reported the qualitative results of the analysis and the framework for the quantitative SWOT analysis, which will be performed at the next step of this study using statistical multivariate analysis.

Keywords: CCUS cluster; CO_2 emission sources; CO_2 storage site; CCS infrastructure; CCS regulations; SWOT analysis; Baltic Region; Mediterranean Region

1. Introduction

Today, CCUS projects around the world inject about 49 million tons of CO_2 underground for geological storage annually. To reach climate neutrality we must increase CO_2 storage from millions to billions of tons annually. CCUS clusters and hubs are one of the options to accelerate this needed scale-up. Application of CCUS clusters and hubs have several advantages: faster scale-up, a decrease of the unit cost, reduction in the risk of investment and cross-chain risk, governmental support, new jobs, CO_2 use revenues, synergy with renewables and CO_2 negative technologies, increased public awareness and improved perception.

This study proposes a framework for initial screening of the most promising national and cross-border CCUS clusters and hubs (value chains). The framework, developed by the Horizon Europe CCUS-ZEN project, is applied to eight case studies in the Baltic and Mediterranean Sea regions.

2. Data and methods

2.1. Data

Technical and non-technical data were first collected and integrated into a common GIS project for eight countries in the Baltic region and five countries in the Mediterranean region (Fig. 1). Technical data includes layers with large CO_2 emissions sources, CO_2 storage sites, available pipeline infrastructure and Natura 2000 areas (Fig. 1, [1]). Qualitative non-technical data were collected via literature searches, as well as expert judgment for key dimensions of readiness across social, regulatory (Fig. 2), political, MRV, and financial issues [2]. Eight large CCUS cluster projects, four in each studied region (Table 1), were selected for more detailed technical analysis, integration with CO_2 use options, and non-technical parameters [3].

Nomenclature

CCUS	CO_2 capture, transport, use and geological storage technology to mitigate climate change approved by EC
CO_2	Carbon Dioxide
H_2	Hydrogen
GIS	Geographical Information System
IMO	International Maritime Organization
LP	London Protocol
MRV	Monitoring Reporting and Verification
Natura 2000	A network of protected areas across the European Union aiming to conserve Europe's most valuable and endangered species and habitats.
PCI	Projects of Common Interest
SRL	Storage Readiness Level
SWOT	Strategic planning technique used to identify strengths, weaknesses, opportunities, and threats related to project planning
ZEN	Zero Emission Network

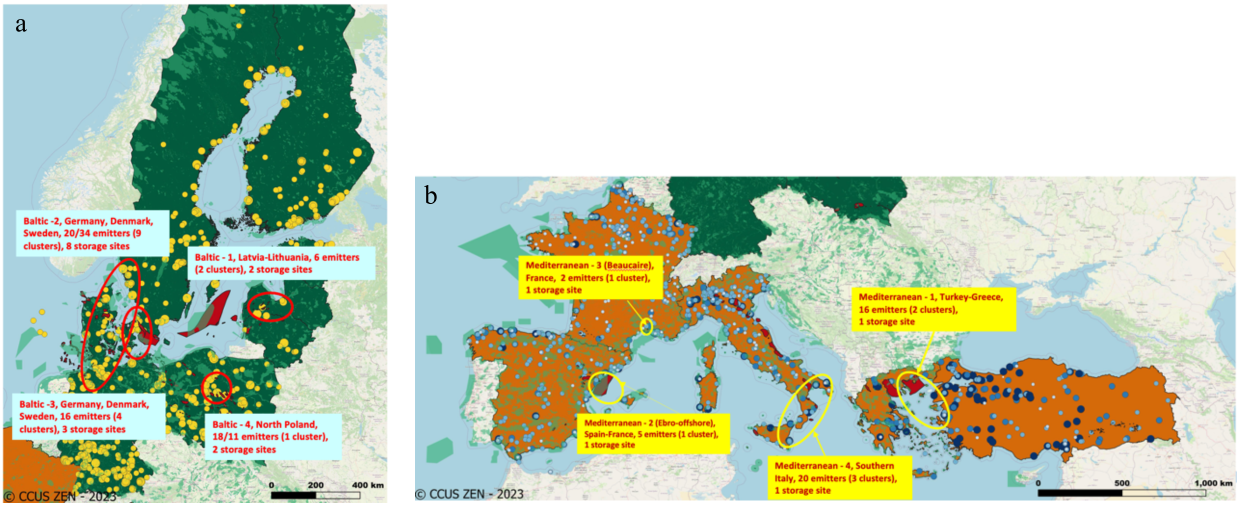

Figure 1. (a) The Location of 4 projects in the Baltic Sea Region selected for Cluster analysis is shown by red ellipse lines; yellow filled circles are CO_2 emission sources, red filled areas are storage sites; (b) Location of 4 projects selected for Cluster analysis in the Mediterranean Sea Region is shown by yellow ellipse lines, blue filled circles are CO_2 emission sources, red filled areas are storage sites.

Table 1. Technical parameters of the eight value chains in the Baltic and Mediterranean Regions selected for analysis

CCUS ZEN Region	Value chain name	Involved countries	Total produced CO_2 emissions, Mt/y	Number of CO_2 sources	Number of CO_2 clusters	CO_2 captured/ CO_2 used, Mt/y	Storage sites name	Estimated CO_2 storage capacity, Mt	Total years for storage	Distance from CO_2 sources to storage sites (min–max), km
Baltic-1	Baltic Lat-Lit-onshore	Latvia Lithuania	4.25	6	2	4.04/0.4	North Blidene, Blidene and Dobele	403	>40	9–150
Baltic-2	DE DK SWE Jutland network	Germany, Denmark, Sweden	22.86	34	9	20.14/6.1	Gassum, Voldum, Jammerbugt, Inez, Bifrost, Greensand, Lisa, Thorning	928	>40	5–750
Baltic-3	Copenhagen	Germany Denmark Sweden	5.9	16	4	5.62/0.56	Rødby, Havnsø, Stenlille	657	>40	5–115
Baltic-4	North Poland onshore	Poland	8.19	11	4	7.78/0.78	Konary J, Kamionki K	381	52	4.2–38.2
Mediterranean-1	Soma - İzmir Aliağa - Prinos	Türkiye Greece	40.0	16	2	18.64/5.59	Prinos	1000	25	120–360
Mediterranean-2	Ebro offshore	Spain and France	23.82	32	3	9.77/2.93	Castellon	200	20	50–470
Mediterranean-3	Beaucaire	France	1.17	2	1	0.833/0.25	Haut d'Albaron	34	29	27
Mediterranean-4	Southern Italy and Athens, Greece	Italy and Greece	41.1	32	6	18.47/5.54	Bradanica	344–1376	7.8–19	50–450

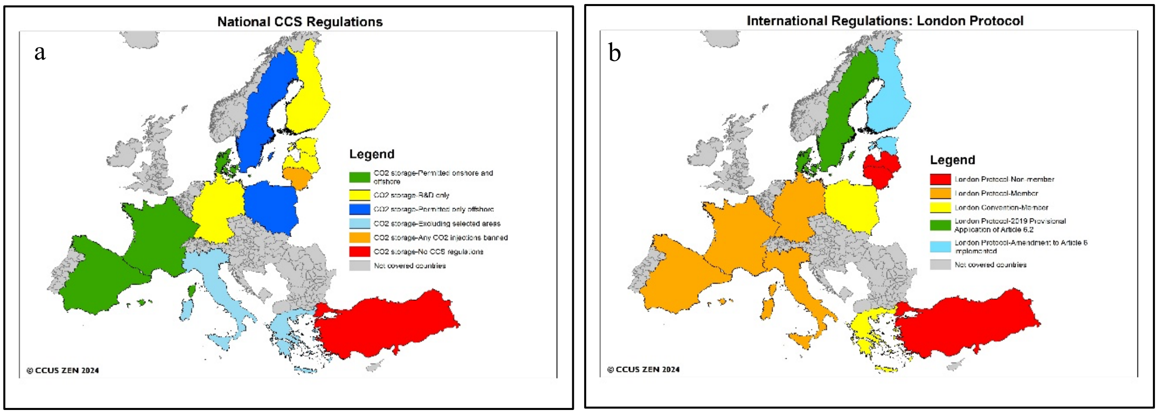

Figure 2. Examples of non-technical data layers are (a) National CCS regulations and (b) International regulations: London Protocol and related issues collected for the Baltic and Mediterranean Regions.

2.2 Methodology of SWOT analysis

SWOT analysis is a strategic planning technique used to identify strengths, weaknesses, opportunities, and threats related to project planning. A SWOT analysis was conducted for prospective CCUS cluster projects encompassing technical and non-technical parameters. The internal group includes aspects characterised by the project's strengths and weaknesses, while the external group includes aspects characterising external opportunities and threats (risks). In this study, we assumed that internal parameters are the most important technical groups composing the various parts of the CCUS value chains. In contrast, external parameters are related to the larger area around the storage site (technical) or the whole country (non-technical).

The methodology reported and applied in [4] could be used to quantify SWOT analysis. The Quantified SWOT analytical method applies the concept of Multiple-Attribute Decision Making (MADM), using a multi-layer scheme to simplify complicated problems. We need to implement a statistical methodology to analyse both quantitative and qualitative data effectively. In this framework, we propose that the weights assigned to internal and external factors should be the same. The weights of the key factors can be calculated using the Analytic Hierarchy Process (AHP) applied to a SWOT analysis [4].

Internal technical groups (strengths and weaknesses) include (1) CO_2 emission plants, (2) CO_2 storage sites, (3) available and planned infrastructure, and (4) CO_2 use options. An external technical group including (1) characteristics of the area around the storage site and non-technical external groups: (1) social, (2) political development, (3) international and national regulations, (4) MRV, (5) financial parameters, (6) readiness of CCUS value chain - were analysed for opportunities and risks. These parameters are the most sensitive for the implementation of the CCUS value chains.

This comprehensive evaluation helps identify potential challenges and advantages for CCUS projects. The analysis of the technical factors identified several key strengths. For factor (1), we examined the piloting and planning of CO_2 capture, options for CO_2 utilisation, and H_2 production. In factor (2), which focuses on CO_2 storage sites, we assessed the porosity and permeability of reservoir rocks, the quality of the cap rock, CO_2 storage capacity, and the SRL.

For factor (3), which pertains to infrastructure, we analysed the availability of natural gas pipelines, total CO_2 emissions per unit of distance, operational and old abandoned wells, offshore infrastructure, and planned PCI. Lastly, for factor (4), we reviewed CO_2 utilisation projects that are currently operational, in development, or in the R&D phase, as well as the potential amount of CO_2 that could be utilised in the cluster.

The external technical factors analysed for the (1) storage site area include several factors: the storage site's location in a densely populated area, its ownership by landlords, its presence in a seismic risk area, and its proximity to Natura 2000 sites or other protected areas.

Regarding non-technical factors, specifically social and regulatory aspects (2) and (3), the following points were analysed: public acceptance, political developments, compliance with the LP and the Amendment to Article 6, adherence to the EU CCS Directive, and national permissions for CO_2 storage.

For monitoring of emissions and financial considerations, the parameters analysed include readiness for MRV and accounting and the availability of government financial support throughout the value chain (4) and (5).

3. Results

3.1. Framework for SWOT analysis

3.1.1 Internal technical factors

Internal technical factors are originally quantitative parameters, each characterised by its units and polarity (Table 2). Positive polarity shows if the strength is a higher number, and negative polarity shows if the strength is a lower number for factors.

Table 2. Factors considered in the technical aspects of the internal group of SWOT analysis

Internal aspects	Factors	Polarity
CO_2 emission plants	(I1) Number of countries	+
	(I2) Number of clusters	+
	(I3) Number of plants	+
	(I4) Fossil CO_2 emissions (Mt)	+
	(I5) Bio-CO_2 emissions (Mt)	+
	(I6) Captured CO_2 emissions (Mt)	+
	(I7) Number of plants planed CO_2 capture	+
	(I8) Number of plants planning H_2 production	+
CO_2 storage sites	(I9) Number of storage sites	–
	(I10) Porosity of the reservoir rocks (average, decimal)	+
	(I11) Permeability of the reservoir rocks (average, Md)	+
	(I12) Well injectivity (Mt/y)	+
	(I13) Thickness of primary cap rocks, m	+
	(I14) CO_2 storage capacity (total, Mt)	+
	(I15) SRL (1–9)	+
Infrastructure	(I16) Transport distance (max, km)	–
	(I17) Transport distance (total, km)	–
	(I18) Total CO_2 emissions per distance unit (t/km)	+
	(I19) Number of wells in operation	+
	(I20) Number of old abandoned wells	–
	(I21) Number of planned PCI projects	+
CO_2 use options	(I22) Number of CO_2 use projects in operation, or R&D	+
	(I23) Longevity of CO_2 use products (years)	+
	(I24) Bio-CO_2 to be used (Mt)	+

3.1.2 External factors

External factors are originally the qualitative parameters for non-technical (Table 3) and technical aspects (Table 4).

Table 3. Factors considered in the non-technical aspects of the external group of SWOT analysis

Aspects	Factors	Polarity
Public acceptance	(E1) Level of public acceptance: Low–1, Medium–2, High–3	+
Political development	(E2) Political development: Favourable – 4–5, Business as usual – 2–3, Unfavourable – 1	+
International Regulations	(E3) LP: Non-member – 1, Member of London Convention – 2, Member of LP – 3, Amendment to Article 6 to LP implemented – 4, Provisional Application of Article 6 to LP – 5	+

National Regulations	(E4) EU CCS Directive implemented: Any CO_2 injection banned – 1 CO_2 storage permitted for research – 2; CO_2 storage: permitted offshore – 3, permitted onshore – 3, permitted onshore and offshore – 5, No CCS Regulations – 0	+
MRV	(E5) MRV Readiness: Low – 1, Medium – 2, High – 3	+
	(E6) Accounting Readiness: Low – 1, Medium – 2	+
Business Model	(E7) Governmental financial support for CCUS projects: Not available – 0, available, but low – 1, available but could be higher – 2, available significantly – 3	+
Readiness of CCUS value chain	(E8) Value chain readiness: Developing Capture –1, Capture available – 2, Developing Capture & Transport – 2, Capture and transport available – 4, Developing Capture, transport and storage – 3, Capture, transport and storage available – 6, Capture in development, storage is available – 3, None – 0	+
Interaction with other decarbonization technologies	(E9) CCUS in Industrial strategy/plan: Yes – 3, No – 1, No strategy/plan – 0	+

Table 4. Factors considered in the technical aspects (the area around the storage site) of the external group of SWOT analysis

Aspects	Factors	Polarity
Density of population	(E10) Storage site located in the densely populated area Low – 1, medium – 2–3, high – 4	–
Storage site ownership	(E11) Storage site area belonging to landlords: Yes – 4, No – 1	–
Seismicity	(E12) Storage site located in seismic risk area: no seismic risk – 1, low seismic risk – 2, seismic risk in the neighbouring region – 3, average seismic risk – 4, high seismic risk – 5	–
Protected areas	(E13) Storage site located in Natura 2000 area/other protected area: 100% located in the protected area – 5, 50% – 4, 25% – 3, 10% – 2, not located – 1	–
	(E14) Transport routes are going through Natura 2000 area/other protected area: 100% located in the protected area – 5, 50% – 4, 25% – 3, 10% – 2, not located – 1	–

To assign quantities, we created questions that can be answered with numbers ranging from 0 to 6 for non-technical parameters and 1 to 5 for technical ones. We applied positive polarity to the non-technical aspects and negative polarity to the technical external aspects.

3.2 Baltic Projects

3.2.1 Baltic-1 scenario (Latvian–Lithuanian onshore CCUS cluster)

The Baltic-1 onshore cluster includes four of the largest Latvian CO_2 emitters and two Lithuanian plants located close to the Latvian–Lithuanian border (Orlen refinery and Akmenes cement plant, owned by Schwenk, Fig. 3). This cluster will store 3.1 Mt of CO_2 annually (Mt/y) from three plants (Latvian and Lithuanian Schwenk-owned cement plants and Orlen Refinery) in the onshore North Blidene and Blidene structures. Latvian two Latvenergo PP and one Rigas Siltums TP located in the Riga region will transport about 0.95 Mt/y of CO_2 in the Dobele storage site in western Latvia using up to 150 km CO_2 pipelines [5]. 41% of CO_2 emissions in the Baltic-1 cluster are coming from the cement industry. The main advantages of the proposed project are the close location to the onshore storage sites, favourable reservoir properties of Deimena Formation sandstones, explained by low temperatures, high CO_2 density and therefore large storage capacity, high storage readiness level, and the readiness of the main industrial stakeholders to develop CCS projects (Schwenk Latvija, Latvenergo and Orlen). The main challenges of the proposed project are non-technical, including regulatory and social factors, considering that the storage site land is owned by local landlords and the CO_2 storage ban has not yet been raised. Governmental financial support from Latvia and Lithuania is not yet envisaged.

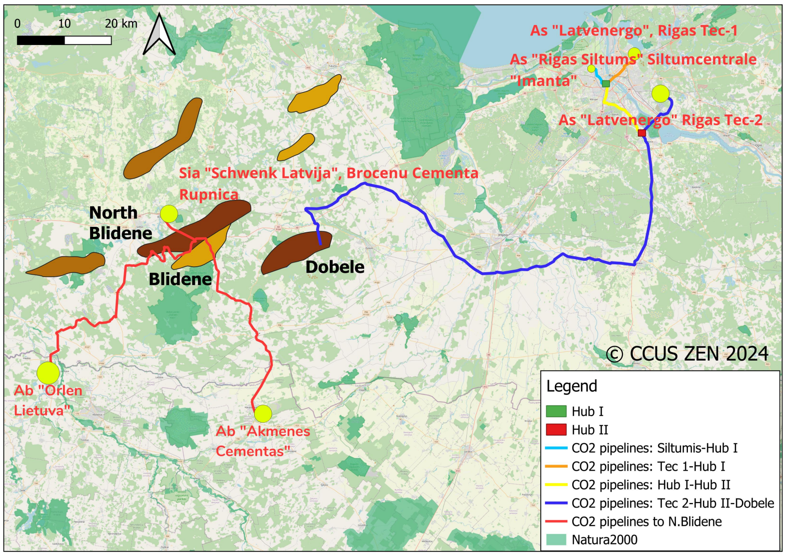

Figure 3. Map of the Baltic-1 scenario with pipeline routes modelled along natural gas pipeline corridors. Latvian Riga cluster of three power plants will transport CO_2 to the Dobele structure. Cement plants from Latvia, Lithuania and Orlen Lithuania will transport CO_2 to the North-Blidene structure in Latvia. The Blidene structure is proposed for H_2 storage.

3.2.2 Baltic-2 scenario

The Baltic-2 project includes nine clusters of 34 emitters from three countries (Denmark, Sweden and Germany) with an annual CO_2 emissions volume of 22.86 Mt/y and respective captured CO_2 volume of 20.1 Mt, from which up to 6.1 Mt will be directed for utilisation. The Baltic-2 combined onshore and offshore cluster offers eight storage sites in Denmark, which have excellent reservoir properties (Fig. 4a). These sites have thick primary cap rocks and a high storage capacity of approximately one gigatonne of CO_2. There are various options for transporting CO_2 from nine emission clusters located across three countries to the eight storage sites, which are situated onshore, nearshore, and offshore. Additionally, CO_2 capture and use options are currently under development, and numerous research and demonstration projects related to CCUS are ongoing in Denmark [6].

The supportive CCS policies, regulations, and financial aid from the government in Denmark, combined with the implementation of international regulations in both Denmark and Sweden, present significant advantages. The two offshore sites are under development by commercial parties. An exploration license has been issued for the onshore Gassum site to Wintershall Dea International GmbH & INEOS E&P A/S. Two CO_2 utilisation pathways (near emitters or intermediate hubs) were explored within this region, converting CO_2 into methanol or synthetic jet fuel [3]. The Swedish FlagshipONE e-methanol project, the largest of its kind in Europe, was recently cancelled by Ørsted in August 2024, and no potential off-takers have been identified. However, Denmark and Germany still have active CO_2 utilisation projects. Notably, the Power-to-Liquid plant at H&R in Hamburg, developed by INERATEC, will produce about 200 tons of e-fuels for transport and 150 tons of e-waxes for cosmetics, pharmaceuticals, and food industries.

The main risk for this project involves international regulations for Germany, which has not yet deposited a declaration of provisional application of the 2009 amendment enabling the export and import of CO_2 for offshore storage under the LP.

3.2.3 *Baltic-3 scenario*

The Baltic-3 project is a cross-border value chain with 5.9 Mt/y of CO_2 emissions produced by 16 plants from Denmark, Sweden and Germany and three storage sites (Havnsø, Stenlille and Rødby) onshore and nearshore Denmark in Zealand and Lolland (Fig. 4b). The total average storage capacity is about 224 Mt CO_2. The distance from CO_2 clusters to storage sites ranges from 5 to 115 km.

Two CO_2 emission clusters in Denmark (Copenhagen and North-western Zealand) produced about 1.9 Mt CO_2 in 2021; the South Sweden cluster produced 1.5 Mt CO_2, and the Rostock cluster produced 2.5 Mt CO_2.

The Baltic-3 combined onshore cluster has three storage sites available. Exploration licenses have been issued for the onshore Havnsø site (Equinor Carbon Solutions Denmark A/S & Ørsted Carbon Solutions A/S) and the Rødby storage site (Carboncuts A/S). The proposed value chain promotes cross-border cooperation for three countries, translating potential investment possibilities being studied today by multiple parties.

The Copenhagen cluster also shows interesting potential for CCU applications, with the (now suspended) Lighthouse project of Green fuels for Denmark receiving IPCEI funding or the Vordingborg port project for producing CCU fuels from captured CO_2 and renewable H_2. The main challenge for this project could be the same as for the Baltic-2 project, connected with international regulations.

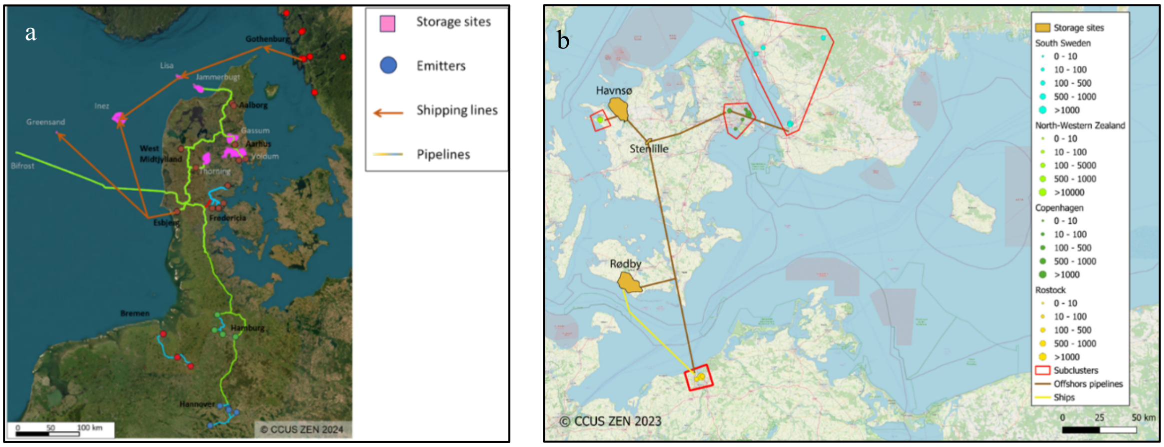

Figure 4. (a) Map of the Baltic-2 scenario showing CO_2 storage locations onshore, nearshore, and offshore. One of the offshore storage sites suggests reusing existing pipelines, while ship transport is assumed for the other offshore and nearshore sites; (b) Map of the Baltic-3 scenario.

3.2.4 Baltic-4 scenario

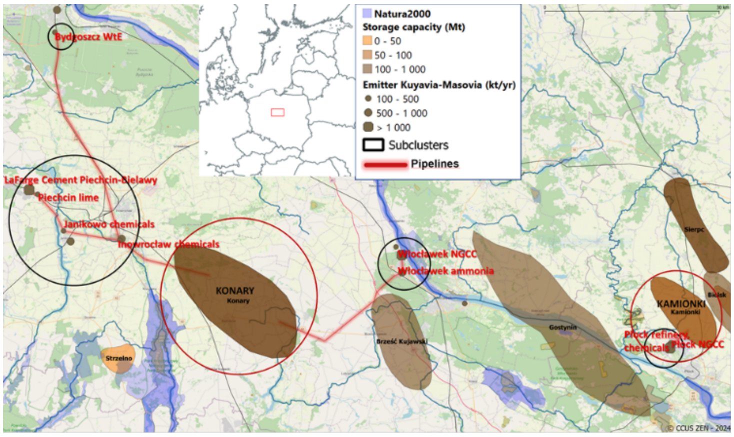

Figure 5. Map of the Baltic-4 scenario with pipeline routes modelled using (where possible) natural gas pipeline corridors.

The Baltic-4 value chain includes the southern cluster of the Northern Poland region, the Kuyavia-Masovia cluster (Fig. 5). There are 18 emitters within the cluster, 11 in the case of old coal-fired energy installations are disregarded. The selected 11 emitters produce 8.19 Mt/y of CO_2 to be captured, stored, or used. Two saline aquifer structures (Konary and Kamionki) located near the four emitter subclusters are proposed as storage sites, where CO_2 can be delivered by pipelines of length 4.2–38.2 km, connecting the emission subclusters and storage sites.

Currently, there is no specific information regarding stakeholder plans for CO_2 usage among emitters in the value chain. However, Orlen's facilities in Płock and Włocławek produce H_2 and generate a relatively pure CO_2 stream as a byproduct, which can be used for various goods. At this moment construction of a CO_2 capture unit is planned in the Płock facility.

Additionally, at the Holcim-Lafarge cement plant, a capture unit is set to be operational in a few years, allowing some of the captured CO_2 to be utilised in concrete production. The value chain area features several onshore saline aquifer structures, with two selected as potential storage sites due to their significant capacity and proximity to industrial emission sources. This allows for easy development and expansion to include more emitters from north-central Poland.

The legal framework for CO_2 onshore storage and transport infrastructure in Poland is expected to be finalised by 2025. Facilities involved in the PCI ECO2CEE project, such as the Orlen refinery and Holcim Lafarge cement plant, may also consider onshore storage as an alternative to the planned railway and shipping transport through the Gdańsk CO_2 terminal to store beneath the North Sea seabed.

3.2.5 Qualitative analysis of the Baltic Projects

After conducting the qualitative SWOT analysis (Tables 3 and 4), we prioritised a list of CCUS value chains based on their level of readiness. Notably, the cross-border Baltic-2 and Baltic-3 CCUS projects emerged as the readiest. The Baltic-2 project centres on both onshore and offshore storage, while the Baltic-3 project is focused exclusively on onshore storage.

The key internal strengths of these two value chains include a high storage capacity due to excellent reservoir properties, the considerable thickness of primary cap rocks, a high density of total emissions per unit distance, and other strong technical parameters. The main external opportunities stem from favourable CCS policies and regulations in Denmark, where CO_2 storage sites are located. Germany, Sweden, and Denmark are Contracting Parties to the LP.

However, Germany faces a significant risk as it has not submitted a declaration for provisional application to the IMO. Such a declaration and a bilateral agreement or arrangement are necessary before Germany can export CO_2 for offshore storage. In contrast, Sweden and Denmark have submitted their declarations and are now able to export CO_2 for offshore storage.

The Baltic-1 and Baltic-4 value chains are categorised as less ready due to regulatory risks associated with CO_2 storage onshore in Latvia and Poland, respectively. Industrial-scale CO_2 storage is not permitted in Latvia. In Poland, CO_2 storage is now permitted offshore in the Baltic Sea. However, due to the prohibition of CO_2 storage in the Baltic Sea by the Helsinki Convention, it is currently not allowed to inject CO_2 offshore in the Baltic. Regulations related to onshore storage are still under development. Despite the planned changes in the CCS regulations and other available technical strengths, these regulatory changes in Latvia and Poland may take additional time, and the risks should be seriously considered.

The Baltic-2 project was selected for further techno-economic modelling and business case in the CCUS ZEN project, based on its highest impact on climate change and the highest level of readiness in the Baltic Region.

3.3 Mediterranean Projects

3.3.1 Mediterranean-1 scenario (M-1)

The M-1 value chain includes two emission clusters - the Soma cluster and the İzmir Aliağa cluster in Turkey, along with an offshore storage site in Greece (Fig. 6). CO_2 emissions from the Soma cluster are transported to İzmir Aliağa via a 120-km pipeline and then shipped to the Prinos storage site, 360 km away.

The M-1 value chain can enhance energy and environmental cooperation between Türkiye and Greece, fostering regional collaboration. Capturing CO_2 emissions from industrial areas like Aliağa and Soma can reduce their climate impact, helping Türkiye meet its Paris Agreement commitments and align with the European Green Deal. Additionally, the Prinos Basin has a good capacity for CO_2 storage, benefiting the local economy and the regional energy sector.

The M-1 value chain encounters several challenges, including technical, economic, social, and regulatory issues.

A major challenge in Türkiye is the lack of accessible annual CO_2 emission data, which forces reliance on IPCC reference approaches for calculations [7]. This reliance can introduce uncertainties in the overall emissions estimates. Furthermore, the seismic activity prevalent in both countries complicates the CO_2 storage process. Establishing new infrastructure, such as pipelines and ships, requires significant investment to ensure feasibility economically, and the absence of carbon pricing mechanisms makes this even harder.

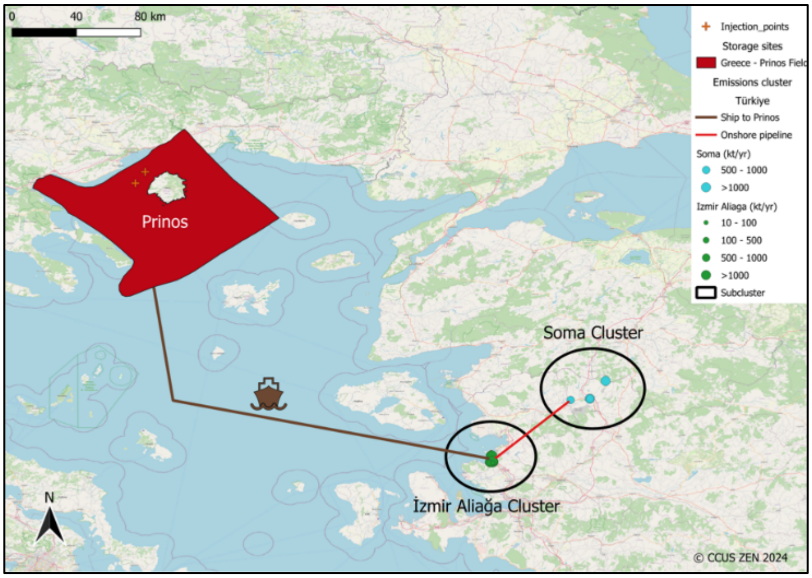

Figure 6. Map of the Mediterranian-1 scenario (M-1).

3.3.2 Mediterranean-2 scenario (M-2)

The M-2 project features three emitter clusters and one offshore storage site in Spain (Fig. 7a, [6]). The Tarragona cluster has five emitters, the Barcelona cluster has 9, and the Fos-Marseille cluster in France has 18 emitters. The geological storage site for CO_2 storage is offshore Tarragona in the Ebro Basin, with a capacity exceeding 200 million tons. The targeted reservoir is in the upper Miocene Castellón Sandstones, which runs from approximately 1600 m to 1900 m and is overlain by the Ebro shales. Additionally, options for CO_2 utilisation are being assessed in France and Spain.

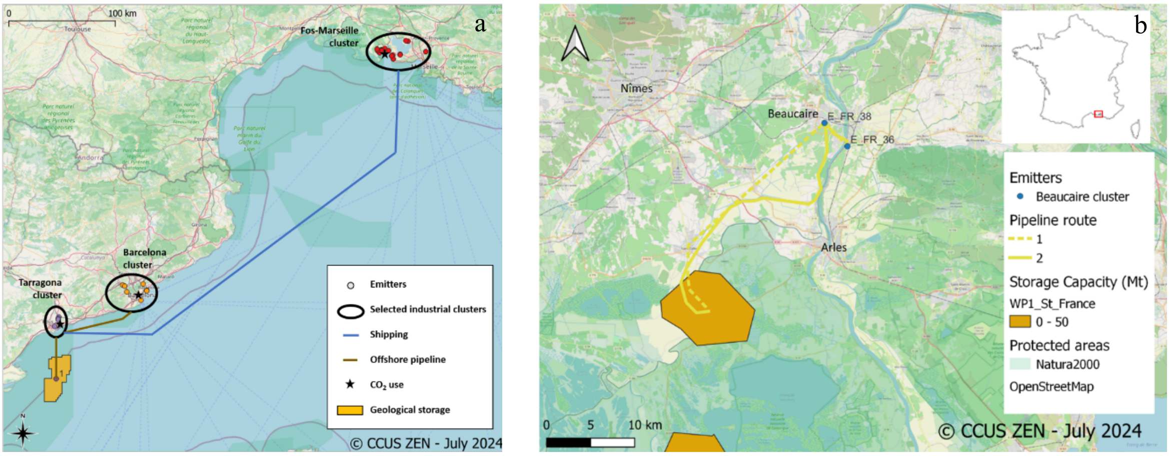

Figure 7. (a) Map of the Mediterranian-2 scenario (M-2); (b) Map of the Mediterranian-3 scenario (M-3).

In the M-2 scenario, the CCU facilities are located near the gathering station within each cluster. The M-2 CCUS value chain can significantly reduce emissions in selected clusters. The Fos-Marseille cluster is ahead in development, as the EU has classified it as a PCI for a CO_2 export terminal. REPSOL EXPLORACIÓN, a Spanish national company, is seeking a permit for CO_2 storage at the Castellón site within the project “TARRACO2”, which would enable offshore CO_2 storage in Spain with a capacity of 200 million tons, sufficient for 20 years of emissions. However, this may challenge the economic viability of the value chain.

3.3.3 Mediterranean-3 scenario (M-3)

The M-3 value chain is a localised project located in Southern France. It incorporates a paper plant and a cement plant near Beaucaire, which together emit 1.17 Mt/y of CO_2. The Haut d'Albaron saline aquifer, located 30 km away, will store up to 34 Mt of CO_2. Onshore pipelines will connect the emitters to the storage site (Fig. 7b).

The storage capacity is tailored to manage emissions from two neighbouring plants, providing a local solution for nearly 30 years. Transport infrastructure investments would be minimal, as distances would not exceed 40 km.

The Haut d'Albaron aquifer, located at a depth of 200 m, allows for CO_2 storage in the gaseous phase. However, despite a thick seal, this limits capacity and raises leakage concerns. Additionally, nearby protected areas, such as Natura 2000 sites and bird protection zones, could complicate the development of CO_2 storage and transportation in the region.

3.3.4 Mediterranean-4 scenario (M-4)

Figure 8. Map of the Mediterranian-4 scenario (M-4).

The M-4 case involves on-land pipelines in southern Italy, extending from Priolo Gargallo to Brindisi (Fig. 8). The Brandanica storage facility is near Taranto. Additionally, ship transport from France and Greece is proposed, with a harbour in Brindisi.

The main advantages for M-4 include a high-capacity CO_2 storage site with effective caprocks and nearby emitter hubs that can utilise pipelines from industrial clusters. Cross-border connections from Greece and France can be integrated, and there are good CO_2 utilisation options in sectors like cement, iron and steel, refineries, and chemicals.

However, challenges exist, including seismic risks in Italy and new regulations that permit experimental storage only in depleted offshore oil and gas fields, with ongoing injections in Ravenna. Additionally, densely populated areas and Natura 2000 sites within the storage zone complicate onshore storage options.

3.3.5 Qualitative Analysis of the Mediterranean Projects

In the Mediterranean Region, Mediterranean-2, -3 and -4 value chains, which include correspondingly emission sources and storage sites in Spain (M-2), France (M-3) and Italy (M-4), are assessed as ready, while M-1, including CO_2 emissions from Türkiye and CO_2 storage in Greece as less ready, considering the regulatory risks. There is a lack of CCS regulations and CO_2 capture and transport infrastructures in Türkiye. Türkiye and Greece are not Contracting Parties to the LP and are therefore not bound by its requirements for cross-border CO_2 transport (i.e. declaration of provisional application and arrangement/agreement). The study closes with an overview of readiness and recommendations for advancing ready and less ready cases toward CCUS implementation. Some projects in both regions also have risks for the storage site area (external group 1).

Italy is planning to implement an Amendment and provisional application to Article 6. However, the technical parameters of the storage site in France M-3 (Haut d'Albaron) are not qualified for the needed requirements (internal technical weakness). Technical risks for the area around the storage site (external group 1) in Italy and Greece: seismic risks should be checked for the storage site areas. Most countries have risks connected with the location of Natura 2000 areas close to the storage sites or intersected with storage sites.

The Mediterranean-2 project was selected for further techno-economic modelling and business case in the CCUS ZEN project based on its relatively high level of readiness and impact on climate change in the Mediterranean Region. The M-4 project has lower readiness, and the M-1 project has the lowest readiness. Both have seismic risks despite a higher impact on climate change compared to the M-2 project (Table 1).

4 Conclusions

Integrated quantitative analysis can be conducted for both offshore and onshore CCUS projects. However, the export of CO_2 to offshore storage sites needs CO_2 storage regulations to be implemented internationally (London Protocol Amendment to article 6) and regionally (Helsinki and Barcelona Conventions), in addition to national regulations and permits needed for CO_2 storage both in onshore and offshore sites.

Despite these differences, a unified quantitative analysis for all projects (both onshore and offshore) can be performed by utilising common internal technical factors and a shortlist of external technical and non-technical parameters.

One area with significant uncertainty involves CO_2 utilisation options. This uncertainty arises from the lack of established regulations for bio-CO_2 emissions, the early stages of project piloting and demonstration, and the uncertain market conditions for CO_2-based products using green energy for production, causing significantly higher costs compared to fossil fuel-based products.

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