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CO_2 storage options in development of CCUS value chain scenarios in northern Poland

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This study builds on the findings of the CCUS ZEN project by focusing on the local storage options of one of the value chains considered in that study, located in the region of northern Poland. Storage options include potential sites in saline aquifers, both onshore and offshore, which have already been screened, selected and evaluated in previous domestic and European projects. The reservoir and caprock parameter data from the literature has been harmonised and validated. The associated uncertainties, knowledge gaps and risks have also been addressed. The standard CSLF methodology for estimating volumetric (static) storage capacity and the Monte Carlo method were used. The storage efficiency factor was then estimated using data on CO_2 injection simulations from the literature. Taken together, these steps go beyond the evaluations carried out in previous projects for these sites. The study shows that deploying and developing such a relatively immature value chain necessitates the integration of technical and non-technical elements, such as legal, social, and policy frameworks. Its focus is specifically on using the local potential for CO_2 storage as an alternative and supplementary measure to shipping. For CCUS planning in Central Europe, it is important that the value chain includes a CO_2 import-export terminal in the Port of Gdańsk. This terminal will eventually be connected to offshore and onshore storage sites via pipelines. The value chain could also be expanded to connect more emission sources and storage sites. This could potentially form part of future regional and pan-European CO_2 storage and CCS infrastructure.

KEYWORDS

CCUS ZEN project, value chain development, CO2 storage in saline aquifer, caprock quality, Central European Basin System, Baltic Sea

1 Introduction

In the context of the industry's decarbonisation efforts, there has been significant research and development in CCS/CCUS technologies. Numerous studies have been conducted worldwide over the past few decades to assess the potential for CO_2 storage and to explore source-to-sink scenarios. A number of regional and case studies were conducted in Europe as part of the GESTCO (Christensen and Larsen, 2004), EU GeoCapacity (Vangkilde-Pedersen et al., 2009), NORDICCS (Anthonsen et al., 2014; Lothe et al., 2016), CO2StoP project (Poulsen et al., 2015) and STRATEGY CCUS (Veloso, 2021) projects. These studies included an assessment of CO_2 storage potential, site screening and preliminary selection, and an evaluation that took into account associated uncertainties. Standardized methodologies and data on specific countries, provided by project partners, were used for these studies. They also explored source-to-sink scenarios. Research in this field has been conducted in numerous domestic and European projects in Poland (e.g., van Bergen et al., 2003; Tarkowski et al., 2006; Willscher et al., 2008; Tarkowski et al., 2009; Dziewińska et al., 2010; Michna and Papiernik, 2012; Wójcicki and Pacześna, 2013; Wójcicki et al., 2014; Wójcicki et al., 2021; Klimkowski et al., 2015; Lubaś et al., 2015; Urych and Smoliński, 2019; Urych et al., 2022; Luboń, 2020; 2021; Szott and Miłek, 2021; Śliwińska et al., 2022; Wojnicki et al., 2023; Miecznik et al., 2025). Nooraiepour et al. (2025) recently summarised studies on CO_2 storage for Poland. As CCS/CCUS technologies continue to advance, the development of CCS/CCUS value chains is increasingly focusing on the integration of industrial emitters with transport and storage hubs and networks (e.g., GCCSI, 2024).

In the CCUS ZEN (Zero Emission Network to facilitate CCUS uptake in industrial clusters) project studies on the development of the CCS/CCUS value chains were carried out. These studies involved integrating clusters of industrial emitters with transport networks and storage hubs in saline aquifers in the regions of the Baltic Sea and the Mediterranean Sea. The CCUS developments in the North Sea region were used as the best practice for the development of new CCUS value chains in both these less developed regions (CCUS ZEN, 2025; Lothe et al., 2025). The CCUS ZEN project considered one of the value chains, which included emission sources in northern Poland, as well as local transport and storage options (Lothe et al., 2025; Wójcicki, 2025).

This paper focuses on the storage part of the value chain, where data from literature have been harmonized and validated. The uncertainties, knowledge gaps, and risks related to the use of storage sites in saline aquifers that were screened, selected, and evaluated in previous domestic and European projects are addressed. Chapter 1.1 briefly characterises the value chain, and Chapter 1.2 presents the geological background, focusing on the storage potential within a broader context. Chapter 2 focuses on knowledge gaps and uncertainties related to the standard volumetric storage capacity assessment used in the CCUS ZEN project and this study. Chapter 3 evaluates storage potential and discusses related uncertainties and sensitivities. This evaluation uses standard Monte Carlo and volumetric storage capacity assessment methodologies and literature. In Chapter 4, risks and barriers pertaining to the implementation of the value chain, particularly the storage part, are discussed.

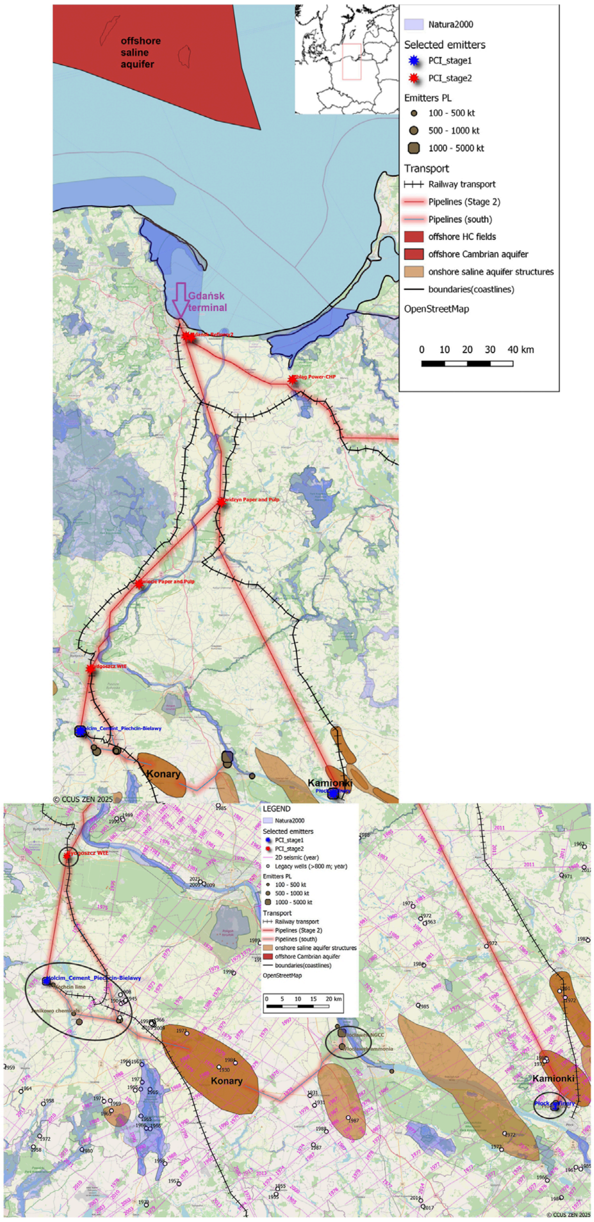

FIGURE 1
The possible integration of the value chain into the next stage of the PCI project (based on Wójcicki, 2025; the southernmost part is enlarged at the bottom). The labelled emitters (in the subclusters encircled) and structures are preferred components of the value chain.

1.1 The value chain

There are 27 emitters in the area with a capacity of at least 0.1 Mtpa each (Figure 1; Wójcicki, 2025). The total capacity is around 22.7 Mtpa. These facilities include refineries, chemical plants, paper and pulp mills, cement production sites and lime kilns, as well as energy industry installations. Excluding old coal-fired energy installations, 16 installations remain, with a total capacity of 14.8 Mtpa (Table 1). The CCUS ZEN value chain in northern Poland is linked to the scope of the ECO_2CEE Project of Common Interest (PCI) on CO_2 terminal in the Port of Gdańsk (Figure 1; Orlen, 2024), as two of these emission sources are also considered in the PCI. In the initial phase of the ECO_2CEE project, which is scheduled to run until 2030, the focus will be on integrating the transport of captured CO_2 by rail from two locations (marked in blue in Figure 1) within the value chain to the terminal: the Orlen Płock refinery (1 Mtpa) and the Holcim cement plant (1 Mtpa; Orlen, 2024). Carbon dioxide delivered to the terminal by rail will be transported by sea and stored in geological structures beneath the North Sea.

However, there is significant storage potential in the region, particularly in the onshore and offshore saline aquifers, which is likely to be sufficient to store CO_2 emissions from local sources. Depending on the timeframe, emitter and storage site

TABLE 1 The proposed storage and transport options for the value chain subclusters (after Wójcicki, 2025). Figure 1 shows the locations.

Emitter subcluster (emissions: Total; selected)	Emission sources (emission [Mtpa])	Storage site	Transport option (approx. distance [km])	Remarks
Bydgoszcz (0.893; 0.164)	Bydgoszcz WtE Energy from waste (0.164)	Konary	Pipeline (38.2 + 16.7)	Bio-CCS possible
	Bydgoszcz Power – CHP (0.729)			Not recommended (old, fossil fuel fired)
Piechcin-Janikowo-Inowrocław (3.442; 1.882)	Holcim Cement Piechcin-Bielawy (1.266)	Konary	Pipeline to Piechcin (1.5)	
	Piechcin lime (0.196)		Pipeline to Janikowo (7.7)	
	Janikowo chemicals (0.179)		Pipeline to Inowrocław hub (9.9)	
	Inowrocław chemicals (0.241)		Pipeline to Konary site (16.7)	Total pipeline length of the subcluster is 35.8 km
	Janikowo Power – CHP (0.723)			Not recommended (old, fossil fuel fired)
	Inowrocław Power – CHP (0.837)			Not recommended (old, fossil fuel fired)
Toruń (0.268; 0.0)	*Toruń Power – CHP (0.269)*			Not recommended (old, fossil fuel fired)
Włocławek (2.048; 1.813)	Włocławek NGCC (1.022)	Konary	Pipeline to ammonia plant (2.8)	Orlen CCS ready CHP plant
	Włocławek ammonia (0.791)		Pipeline to Konary site (27.0)	Orlen hydrogen hub in development; Total pipeline length of the subcluster is 35.8 km
	Włocławek Power – Heating (0.119)			Not recommended (old, fossil fuel fired)
	Włocławek Oil and Gas Processing (0.116)			Not recommended (old, fossil fuel fired)
Płock (6.975; 4.328)	Płock refinery (2.557)	Kamionki	Pipeline to remaining plants in Płock complex (0.7)	Orlen hydrogen hub development, CO_2 use products
	Płock NGCC (0.947)		Pipeline to Kamionki site (3.5)	Orlen CCS ready CHP plant
	Płock chemicals1 (0.721)			
	Płock chemicals2 (0.103)			Total pipeline length of the subcluster is 4.2 km
	Płock Power – CHP (2.647)			Not recommended (old, fossil fuel fired)
Świecie (3.973; 3.973)	Świecie Paper and pulp (3.973)	Cambrian offshore	Onshore pipeline and/or barges floating Vistula river to Gdańsk terminal, ship from the terminal to the site (~245)	Largest biomass-fired installation in Poland
Grudziądz (0.146; 0.0)	*Grudziądz Power – CHP (0.146)*			Not recommended (old, fossil fuel fired)

(Continued on the following page)

TABLE 1 (*Continued*) The proposed storage and transport options for the value chain subclusters (after Wójcicki, 2025). Figure 1 shows the locations.

Emitter subcluster (emissions: Total; selected)	Emission sources (emission [Mtpa])	Storage site	Transport option (approx. distance [km])	Remarks
Kwidzyn (0.687; 0.687)	Kwidzyn Paper and pulp (0.687)	Cambrian offshore PL	Onshore pipeline and/or barges floating Vistula river to Gdańsk terminal, ship from the terminal to the site (~195)	Fossil fuel (hard coal) is gradually replaced with biomass (poplar)
Elbląg (0.223; 0.223)	Elbląg Power – CHP (0.223)	Cambrian offshore PL	Onshore pipeline and/or barge to Gdańsk terminal, ship from the terminal to the site (~200)	The emitter is small but is in process of replacing fossil fuels with biomass
Gdańsk (3.359; 1.727)	Gdańsk Refinery1 (1.516)	Cambrian offshore PL	A short pipeline to Gdańsk terminal, ship from the terminal to the site (~7 + 113)	
	Gdańsk Refinery2 (0.211)			
	Gdańsk Power – CHP1 (1.340)			Not recommended (old, fossil fuel fired)
	Gdańsk Power – CHP2 (0.292)			Not recommended (old, fossil fuel fired)
Gdynia (0.670; 0.0)	*Gdynia Power – CHP (0.670)*			Not recommended (old, fossil fuel fired)
The value chain emitters (22.684; 14.761)				

locations, and volumes of captured carbon dioxide, transport options might include railway, pipelines and/or ship/barge delivery (Gravaud et al., 2023). The current legal framework in Poland allows permits for CO_2 storage to be applied for only in an offshore area (The Ordinance, 2014). However, Article 11 of the Helsinki Convention currently prohibits the storage of CO_2 under the Baltic Sea seabed, and is to be amended (Wammer Østgaard, 2024). The revision of the regulation allowing onshore CO_2 storage in Poland is to be published soon. Regulations on onshore CO_2 transport, particularly those relating to the construction and operation of CO_2 pipelines, are currently being drafted. It is therefore proposed that the next stages of the PCI project include additional CO_2 emitters from the value chain (see Figure 1). At the same time, it is proposed that the original concept of the PCI be supplemented and enhanced by the introduction of additional transport and storage options.

1.2 Geological background with focus on storage potential

The reservoirs and relevant caprocks of the considered onshore saline aquifer structures are within Lower to Middle Jurassic and Cretaceous formations (Dziewińska et al., 2010; Wójcicki et al., 2014). The Lower to Middle Jurassic formations cover more than half of Poland's territory. They are the easternmost part of the Central European Basin System (CEBS; Pieńkowski and Schudack, 2008) and consist of several regional complexes primarily made up of lacustrine, fluvial, shallow marine and deltaic sandstones. These sandstones have usually good reservoir properties. The reservoirs are accompanied by several regional caprock complexes, primarily composed of claystones, mudstones and shales of marine origin. The CEBS includes similar (though not always contemporary) reservoir and caprock formations, present in northern Germany, Denmark, the Netherlands and as far as eastern France, northern Switzerland and parts of England (Pieńkowski and Schudack, 2008). Regional formations of black shales, resulting from marine anoxic events, have the potential to serve as reliable caprocks. For instance, the Lower Toarcian Posidonia shales and their equivalents, which are present in a large part of the CEBS (Pieńkowski and Schudack, 2008; Hesselbo and Pieńkowski, 2011; Pieńkowski, 2015) are of proven very low permeability (Ladage, 2016). The Cretaceous formations considered in the value chain comprise Lower Cretaceous reservoirs, which are primarily made up of sandstones of shallow marine and deltaic origin. The caprock formation comprises thick sequences of Upper Cretaceous limestone, marly limestone, opoka, mudstone and claystone (Dziewińska et al., 2010). These are all of shallow marine or carbonate shelf origin. Similar formations, though not always contemporary, are present in parts of Poland, northern Germany and Denmark (Voigt and Wagreich, 2008; Ladage, 2016; Hjelm et al., 2020).

Another storage option within the value chain is the offshore Cambrian saline aquifer in the north-eastern part of Poland's Baltic Sea sector. This contains several relatively small hydrocarbon fields. The reservoirs (Semyrka et al., 2010) are primarily composed of Middle Cambrian sandstones of shallow marine, clastic origin, while the caprock comprises a thick, claystone-shale-carbonate sequence of Upper Cambrian, Ordovician, and Silurian rocks of marine origin. The aquifer is part of the Cambrian sandstone formation, which can be found in the south-eastern Baltic Sea and the surrounding land areas (Nilsson, 2014; Vernon et al., 2013; Mortensen and Sopher, 2021). The primary seal of the Cambrian sandstone reservoir is the Alum Shale Formation, or equivalent formations of the Upper Cambrian and Lower Ordovician periods, which are proven to have very low permeability (Poprawa, 2020; Schulz et al., 2021).

2 Method, materials and knowledge gaps

2.1 Emission sources and transport options

The inventory of industrial emission sources was completed in the CCUS ZEN project (Ringstad et al., 2023; Lothe et al., 2024; 2025; CCUS ZEN website). The Polish part of the pan-European database provided by one of the project partners (ENDRAVA) was verified, updated and amended using data from the European Union Registry (European Commission, 2025), previous projects (e.g., Tarkowski et al., 2009; Wójcicki et al., 2014) as well as company websites and press releases. The relevant information on the emitters in the studied region is included in Table 1.

The transport routes presented in Figure 1 have been drawn using the CCUS ZEN GIS project (Ringstad et al., 2023; Gravaud et al., 2023). The GIS included the publicly available existing gas pipeline and railway routes, as well as nature protected areas. These features have been taken into consideration when drawing the proposed transport routes. According to Ho et al. (2024), the rail transport of liquefied carbon dioxide is safer than onshore pipeline and truck transport when the number of incidents in the US between 2003 and 2023 is considered. The volume of CO_2 released in railway incidents per year is also over sixty times smaller than in pipelines. However, it should be noted that rail transport is used for smaller amounts of CO_2 over shorter distances than pipelines. The adaptation of legacy gas pipelines was excluded from this study. It was assumed that using the existing pipeline routes would make designing the new ones easier. Neither the CCUS ZEN project nor this study considered the technical specifications of new pipelines for the value chain. However, to avoid pipeline corrosion, the CO_2 stream must not contain any significant quantities of certain admixtures, particularly water, as well as SO_x, O_2, NO_x and H_2S, which could form corrosive acids and solutions. Danish Energy Agency (2024), the Northern Lights project specifications require that the CO_2 stream delivered to the pipeline eventually includes: $H_2O \leq 30$ ppm, $O_2 \leq 10$ ppm, $SO_x \leq 10$ ppm, $NO_x \leq 10$ ppm and $H_2S \leq 9$ ppm.

2.2 Storage potential

In the CCUS ZEN project, potential storage sites that had been screened and selected in previous European and national projects within the considered regions were described and evaluated (Lothe et al., 2024; 2025). This evaluation was focused particularly on saline aquifers, which are the option with the highest storage potential. This included indicating the maturity of the storage site capacity evaluation, as defined by Akhurst et al. (2021). The standard CSLF methodology for the volumetric (static) storage capacity assessment of saline aquifers (after Vangkilde-Pedersen et al., 2009) was applied using the following formula:

$$M_{CO2} = A \times h \times NG \times \phi \times \rho_{CO2r} \times S_{eff}$$

where:

M_{CO2}: regional or trap aquifer storage capacity,
A: area of regional or trap aquifer,
h: average thickness of regional or trap aquifer,
NG: average net to gross ratio of regional or trap aquifer,
ϕ: average reservoir porosity of regional or trap aquifer,
ρ_{CO2r}: CO_2 density at reservoir conditions,
$Seff$: storage efficiency factor.

For regional saline aquifers, the recommended storage efficiency factor is approximately 2%. For traps, the recommended storage efficiency values for semi-closed low-quality and open high-quality reservoirs are between 3% and 40%, respectively (Vangkilde-Pedersen et al., 2009). This factor implicitly considers the effects of non-reducible water saturation, and likely capillary trapping, in addition to structural and hydrodynamic trapping. Thus, it is equivalent to the US Department of Energy methodology (Goodman et al., 2011), which uses injection simulation results and related uncertainties to estimate the factor.

A similar approach was applied in the recent study on CO_2 storage potential in Denmark (Hjelm et al., 2020), but the modified storage efficiency factor excluding reservoir volume below the spill point and the CO_2-water contact was considered. Furthermore, the Monte-Carlo simulation method was employed to assess the capacity uncertainty range. Bachu (2015) highlighted that the CSLF approach might lack reliability unless it is validated by CO_2 injection simulations for the storage site's lifetime and beyond (dynamic storage capacity). Recent CSLF studies (CSLF, 2019; CSLF, 2021) emphasize the importance of validating the approach using injection simulations and field injection data. In addition to the structural, stratigraphic, hydrodynamic and capillary trapping mechanisms, they also recommend considering the dissolution and solubility, as well as the mineral trapping, mechanisms to ensure the safe storage of CO_2 in the storage complex. It should be noted that different time scales apply to the respective mechanisms, depending on the storage complex's lithology. For example, the mineral trapping mechanism is negligible in the short term in sandstone reservoirs, which are considered in this study. On the other hand, mineral CO_2 trapping is a dominant, relatively short-term storage mechanism in saline aquifers in mafic basaltic formations because these rocks are composed of highly reactive minerals such as plagioclase, wollastonite, pyroxene, and olivine (Al Maqbali et al., 2023). Another story is the *in situ* CO_2-EOR operation involving the interaction of fluids within an oil field (Hussain et al., 2021). In this process, temperature controls the rate at which a CO_2-generating chemical agent hydrolyses, as well as the solubility of CO_2 in the oil and water phases (Hussain et al., 2023).

The most recent reports from the International Energy Agency's Greenhouse Gas R&D Programme (IEAGHG, 2024; 2025) summarise and discuss current global developments in the field of safety evaluation of CO_2 geological storage in saline aquifers. They emphasise the importance of evaluating the containment of the storage site, taking into account factors such as seal capacity, hydraulic fractures, fault sealing and overpressure caused by CO_2 injection in the models, as well as the integrity of new and legacy wells. Large-scale CO_2 storage requires modelling the capacity and integrity of the storage complex over the long term, at both local and larger scales. This involves considering multiple reservoirs, caprocks and faults in the local area and beyond (Gilmore et al., 2022; Kivi et al., 2022). Seal capacity assessment involves more than measuring capillary breakthrough pressure, wettability, and the impact of injected CO_2 temperature (Espinoza and Santamarina, 2017). Knowledge of *in situ* stress is crucial and can be obtained through borehole geomechanical testing. Together with well logging, laboratory testing of rock samples, and seismic interpretation, borehole geomechanical testing can provide input for geomechanical modeling (Thompson et al., 2022). Another important factor is the long-term impact of geochemical reactions between CO_2, brine, and caprock on sealing mechanisms. In some cases, these reactions may improve the sealing properties of the caprock (Yang et al., 2020). Minerals that are particularly susceptible to dissolution include calcite, olivine, pyroxene, anorthite, and berthierine (Watson, 2012). The presence of existing faults or fractures, which form during or after the injection period, may expedite geochemical reactions and caprock disintegration due to CO_2 flow (Dean et al., 2020; IEAGHG, 2024). The complexity of the interaction between chemical, mechanical, hydraulic, and thermal aspects, as presented above, requires a comprehensive modeling approach to address caprock integrity during long-term CO_2 storage (IEAGHG, 2024). This approach may involve coupling or sequencing the modelled processes (Alsayah and Rigby, 2023; Yong et al., 2019).

In this study the standard CSLF methodology for the volumetric (static) storage capacity assessment of saline aquifers was used as well. The structures considered in this study were screened, selected and evaluated in previous domestic and European projects (Tarkowski et al., 2009; Vangkilde-Pedersen et al., 2009; Dziewińska et al., 2010; Wójcicki et al., 2014; Poulsen et al., 2015; Lothe et al., 2025), in which the same methodologies for assessing volumetric storage capacity were employed. The selection of suitable structures in saline aquifers was based on the guidelines set out by Chadwick et al. (2008). Chadwick et al. (2008) state that the key geological indicators for determining the suitability of a storage site include caprock efficacy, reservoir efficacy and properties. The caprock efficacy considers such parameters as the lateral continuity, thickness and capillary breakthrough pressure of rocks deemed to be sufficiently impermeable. In this study, data from literature, including the results of these previous projects and other publications, have been harmonised and validated. The relevant results of the reservoir simulations (Luboń, 2020; Luboń, 2021; Wojnicki et al., 2023) were used to estimate the storage efficiency factor in the volumetric storage capacity assessment. Chapter 2.1 presents information and data on the capillary breakthrough pressure of Jurassic and other Mesozoic caprocks in the Polish Basin, as well as the permeabilities of caprock analogs. The data range of the capillary breakthrough pressure is consistent with the values assumed in the reservoir simulations of Luboń (2020), Luboń (2021). Chapter 2.1 also discusses laboratory experiments and long-term geochemical simulations of the brine-rock-CO_2 system, which were conducted using rock samples from Mesozoic aquifers and caprocks from the Polish Basin. The results suggest that the contribution of mineral trapping to storage capacity is significant only over timeframes measured in thousands of years. Therefore, this mechanism was not considered in the storage efficiency factor in this study. The results also suggest that the long-term impact of geochemical reactions on the reservoir and caprock sealing properties is not significant. However, there are no published results from geomechanical modelling of sites with similar geological conditions. Furthermore, there are no relevant simulations that take into account the interaction between the chemical, mechanical, hydraulic and thermal aspects of storage complexes during and after injection.

Standard Monte Carlo method was used with the simulation tool built in the open source Gnumeric software (Baudais et al., 2012). Simple distributions available in the software were used as input for the simulations, i.e., a normal distribution was assumed for all parameters except porosity, which was lognormal. The estimated uncertainty ranges correspond to ±3 standard deviations from the mean values of the parameter distributions. The CSLF formula presented above was implemented in the simulation tool. To achieve stable and sufficient statistical representation of both input distribution and result output, 10,000 iterations were calculated for each simulation.

Therefore, the general conclusion is that the sites considered in this study are quite immature according to the standards defined by Akhurst et al. (2021). In other words, the findings of this study may help plan the appraisal phase. The recent developments in storage safety evaluation should be considered during the appraisal and characterisation phases. Due to concerns raised by stakeholders about the safety of CO_2 storage, the issue of the long-term integrity of the seal should be addressed during the appraisal and characterisation phases.

2.3 Review of knowledge about seal quality and storage complex reactivity relevant to the considered storage sites

2.3.1 Seal quality

According to the literature, the primary seal permeability is generally assumed to be in the micro- to nano-Darcy range. However, a value that is too low could cause excessive pressure (Bachu, 2015; Espinoza and Santamarina, 2017; Rackley and Rackley, 2017). Therefore, the practical range of this parameter could be 0.0001–0.005 mD. However, these values are below the accuracy of the mercury porosimetry method, which was commonly used for samples from legacy wells.

Such low permeabilities have been particularly measured on gas-bearing shale samples where methods employing various gases instead of mercury are used (Schulz et al., 2021). Methods of determining the capillary breakthrough pressure of caprock samples at simulated reservoir conditions (Soomro et al., 2025) generally rely on similar assumptions. Therefore, both permeability and capillary breakthrough pressure values were determined in laboratory experiments for a limited number of fine-grained caprock samples in the Polish national project. These experiments suggest that the capillary breakthrough pressures of the main (onshore) caprocks in the Polish basin exceed 25% of the relevant reservoir pressures. In other words, the capillary pressures are within the range of 2.6–7.2 MPa at a reservoir depth of 1–2 km, with a pressure close to the hydrostatic pressure (Smulski et al., 2013). The measured permeabilities of these caprocks are in the micro-Darcy range. This means that they make a good containment provided there is no faulting. Studies on Posidonia shale of Lower Jurassic in Germany, which is an equivalent of one of principal caprocks in the Polish basin, also suggest the permeability in the micro-Darcy range (Ladage, 2016). The measured permeabilities of the Upper Cambrian-Ordovician shales, which form the caprock for the Middle Cambrian aquifer in the Baltic basin, are even one order of magnitude lower (Poprawa, 2020; Schulz et al., 2021). This means they could make even better containment.

2.3.2 Geochemical analyses and modelling

Tarkowski and Wdowin (2011) carried out laboratory experiments on the interactions between injected CO_2, rocks and brines, using rock samples from Lower Cretaceous and Lower Jurassic sandstone reservoirs and carbonate caprocks from the Polish Basin. The experiments did not significantly worsen the reservoir properties of the rocks. These likely slightly improved the sealing capacity of the caprocks. Several studies have carried out long-term geochemical simulations of the brine-rock-CO_2 system in Jurassic sandstone reservoirs and claystone caprocks, based on laboratory analyses and experiments (e.g., Tarkowski et al., 2011; Labus et al., 2014). According to these findings, the disintegration of kaolinite slightly increases the reservoir's porosity at the start of the 20,000-year modeling period. Then, the precipitation and crystallisation of carbonate minerals decrease porosity, which remains relatively unchanged for the rest of the period. During this time, kaolinite, chalcedony and quartz recrystallise. In the caprock, plagioclase dissolution is followed by beidellite and gibbsite crystallisation, then by carbonate minerals and kaolinite crystallisation. During the 20,000-year modeling period, it was estimated that trapping in carbonate minerals (dawsonite, calcite, siderite, and dolomite) could sequester up to 12 kg of CO_2 per cubic meter of formation in reservoirs and up to 15.4 kg of CO_2 per cubic meter of caprock. These processes do not significantly impair the properties of the reservoir rocks and may even slightly enhance the sealing properties of the caprock (Tarkowski et al., 2011; Labus et al., 2014).

The results of these studies are broadly consistent with existing knowledge of the mineral composition of the reservoirs in question, particularly with regard to the presence of reactive minerals (Kozłowska and Kuberska, 2014). In Jurassic sandstone reservoirs, calcite appears as a small admixture in the cement that binds the matrix of clay minerals and larger grains together. This cement typically consists of quartz, siderite, and ankerite. The grains are mostly composed of quartz and alkali feldspar and occasionally contain plagioclase and mica.

3 Results

3.1 Onshore CO_2 storage options

The southern part of the value chain area (Figure 1), where two ECO$_2$CEE emitters and several others are located, contains several saline aquifer structures in Jurassic and Lower Cretaceous sandstones of good reservoir quality. These structures were screened, selected, and evaluated in previous domestic and European projects.

Published data on the results of reservoir tests of Lower and Middle Jurassic sandstones, and Lower Cretaceous sandstones, carried out using formation testers, are available for several wells located within the area (Dembowska and Marek, 1985; Feldman-Olszewska, 2007; Feldman-Olszewska, 2008). Brine yields of 0.9–14.96 m^3/h were reported in the Lower Jurassic sandstones, 3.55–30 m^3/h in the Middle Jurassic, and around 30 m^3/h in the Lower Cretaceous. These results confirm the quality of reservoirs. In the SSE part of the area, gas and oil shows have been observed in the Jurassic and Cretaceous formations. No meaningful overpressure is observed within these reservoirs.

The estimated volumetric storage capacities of these structures, calculated in several projects using the CSLF methodology (Tarkowski et al., 2009; Dziewińska et al., 2010; Wójcicki et al., 2014; Poulsen et al., 2015; Ringstad et al., 2023), are significantly exceeding the possible demand of all emitters of the local cluster (Table 1), i.e., the estimated volumetric capacity of all the onshore structures shown in Figure 1 is within the approximate range of 1.5–2 Gt. Due to the proximity of the emitters and potential storage sites, the development of storage and transport infrastructure could be relatively cost-effective in this area.

Two saline aquifer structures, Konary and Kamionki, have been identified as potential storage sites within the value chain. Both structures are located in close proximity to CO_2 emitter subclusters (see Figure 1). There are no protected areas or major settlements above the structures, nor are there any conflicting activities above the storage complex. At the fully industrial stage of the value chain, transport via new onshore pipelines is proposed. In the event of the pilot injection or at the preliminary stage, railway or road transport might be a viable option. Depending on the particular emitters and emitter subclusters in question, the estimated length of pipeline sections in the southern part of the region ranges from 4.2 to 38.2 km (Table 1). The Konary structure is proposed as the storage site for three nearby subclusters. One is located to the west and incorporates the Holcim cement plant, which is included in the first stage of the ECO$_2$CEE PCI project. Another is located north-west, and the last is to the east of the structure (Figure 1). The Kamionki structure is proposed for use as the storage site for the nearby emitter subcluster, which includes, among other elements, the Orlen Płock refinery. The refinery is scheduled to be in the first stage of the ECO$_2$CEE PCI.

3.1.1 The Konary structure

The Konary structure is a brachyanticline that was formed above a Zechstein salt pillow. It encompasses a multi-reservoir Jurassic aquifer (Figures 2A,B). This aquifer consists of sandstones from the Lower Aalenian, Upper Toarcian, Pliensbachian, and Sinemurian periods. These sandstones are separated by seals or aquitards. However, the Lower Aalenian-Upper Toarcian reservoir exceeds the CO_2 supercritical range at the structure's summit (Luboń, 2020; Wójcicki et al., 2014; Figures 2B–D), so only Pliensbachian and Sinemurian reservoirs are considered. The primary caprock/seal consists of Lower Toarcian black shales (i.e., claystones and mudstones), while the additional seals comprise Bajocian and

Upper Aalenian claystones and mudstones, as well as Bathonian claystones (Figure 2B).

The structure was drilled by two legacy wells with well logs in 1973 and 1984 (Figure 1) and explored by over twenty 2D seismic lines (in the 1970-90s) of varied quality. These lines were shot for hydrocarbon prospecting in far deeper Permian formations. Due to concerns regarding data quality and coverage, it should be noted that there are potential risks related to trapping efficiency, closure and caprock. According to the legacy seismic survey, no faults were identified within the caprock. However, there is one close to the NE edge of the structure, according to Dziewińska et al. (2010) (Figure 2A). In a recently completed project by the state geological survey, a few legacy seismic lines were reprocessed and reinterpreted (Kijewska, 2024; see Figures 2C,D). Although no visible faults were detected, the quality of the legacy seismic data was insufficient to detect small faults within the structure's summit. Additionally, the amplitude of the structure in the north-west (Figure 2D) raises the question of whether the closure and structural trapping efficiency are sufficient.

The values and uncertainty ranges of reservoir and caprock parameters presented in Table 2 have been assumed based on legacy data and information available for the structure or structures and formations in similar geological conditions (same or equivalent formation and depositional environment, similar depth range and diagenesis stage). The area was assumed after Wójcicki et al. (2014), where it was estimated using legacy seismic maps. The cumulative thickness of the Pliensbachian-Sinemurian aquifers and their net-to-gross ratio were estimated using profiles and correlations of boreholes within and near the structure, as presented by Feldman-Olszewska (2013), Feldman-Olszewska et al. (2010), Feldman-Olszewska et al. (2012) and Dziewińska et al. (2010). The effective porosity was estimated using the results of laboratory measurements of rock samples taken from boreholes within and near the structure, as well as the results of laboratory measurements and well logging interpretations of boreholes located further away, but in similar geological conditions (Feldman-Olszewska, 2013; Feldman-Olszewska et al., 2010; Feldman-Olszewska et al., 2012; Kozłowska and Kuberska, 2014). Similarly, the representative permeability was estimated. This is not included in the CSLF formula (Vangkilde-Pedersen et al., 2009), but it indicates reservoir quality and injectivity. The CO_2 density was estimated using an online calculator, based on the estimated mean pressure and temperature within the Pliensbachian-Sinemurian aquifer at the top of the structure. For the mean pressure estimation, hydrostatic pressure was assumed, as well as the depth after the legacy seismic maps and borehole profiles within the structure. The temperature was estimated using data from the geothermal atlas by Górecki (2006). In the estimation of storage efficiency factor, concerns raised by Bachu (2015) were taken into account. That is to say, such parameter should be validated by reservoir simulations. However, the availability, quality and usability of these simulations is limited in our case.

Recently, Luboń (2020), Luboń (2021) carried out injection simulations based on a simple geological model of the reservoir and data from one legacy well. The author calculated the single injection well storage capacity of the Pliensbachian reservoir at the summit of the structure (no deeper than 1000 m b.s.l.) to be between 10.2–15.5 Mt, depending on the assumed capillary pressure at the top of the reservoir and assumed faulting, and up to 49.9 Mt when the pressure parameter is not taken into consideration. The former values correspond to a storage efficiency factor range of 4.23%–6.44% (average 5%; Luboń, 2021), while the latter most likely corresponds to a factor of around 20.8%. These values were assumed as the uncertainty range in Table. Urych et al. (2022) conducted injection simulations in a Jurassic saline aquifer structure in northwestern Poland under similar geological conditions. These were hydraulic models based on clay content, porosity, and permeability data from boreholes within and near structures, similar to case studies of the national project (Wójcicki et al., 2014). However, rather than assessing the maximum safe dynamic storage capacity, they assumed the amount of CO_2 injected per well and globally. Therefore, these simulations cannot be used to estimate the storage efficiency factor.

Caprock was not included in Luboń (2020), Luboń (2021) model, and its parameters are not included in the CSLF formula. However, they are critical to evaluating the structure. The available caprock data and information presented in Table 2 includes lithology, thickness, and representative permeability and porosity. Information on the thickness and lithology of the caprock within and around the structure comes from Feldman-Olszewska (2013) and Feldman-Olszewska et al. (2010), Feldman-Olszewska et al. (2012). So does porosity where also data from boreholes located further away, but in similar geological conditions were taken into account because of limited availability of such data within and around the structure. Due to the relatively low accuracy of available laboratory measurements of the permeability of rock samples from legacy wells within and around the structure (Feldman-Olszewska, 2013), data from analogs is assumed (Ladage, 2016; Smulski et al., 2013).

The inputs of the Monte Carlo simulations were based on similar assumptions as in Hjelm et al. (2020). The standard methodology of the open-source software (Baudais et al., 2012) and the standard CSLF formula (Vangkilde-Pedersen et al., 2009) were used. A simple sensitivity analysis is included in Table 2. It shows that uncertainty in the storage efficiency factor has the greatest influence on the calculated volumetric storage capacity. The simulations provided an assessment of the storage capacity (Table 2) corresponding to the emissions of the nearby industrial installations (total: 3.859 Mtpa) over a period of between 24 and 127 years (median: 60 years).

3.1.2 The Kamionki structure

The Kamionki structure comprises two reservoirs: the Lower Cretaceous sandstones (the primary) and the Lower Aalenian-Upper Toarcian (the backup) sandstones (Dziewińska et al., 2010; Feldman-Olszewska et al., 2012; Wójcicki et al., 2014; Figure 2E). The caprock is a thick sequence of Upper Cretaceous marls and marly limestones.

The structure was drilled by three legacy wells in 1972, 1973 and 1987 (see Figures 1, 2E) and explored by over twenty 2D seismic lines (in the 1970-90s) of varied quality. There are potential risks associated with trapping efficiency, closure and caprock integrity. The structure in Figure 2E appears to have a low amplitude. However, the section is close to three legacy wells located near the northeast tip of the structure (see Figure 1). As the Upper Cretaceous caprock is mostly composed of carbonate minerals, its sealing effect depends on the chemical reaction between dissolved

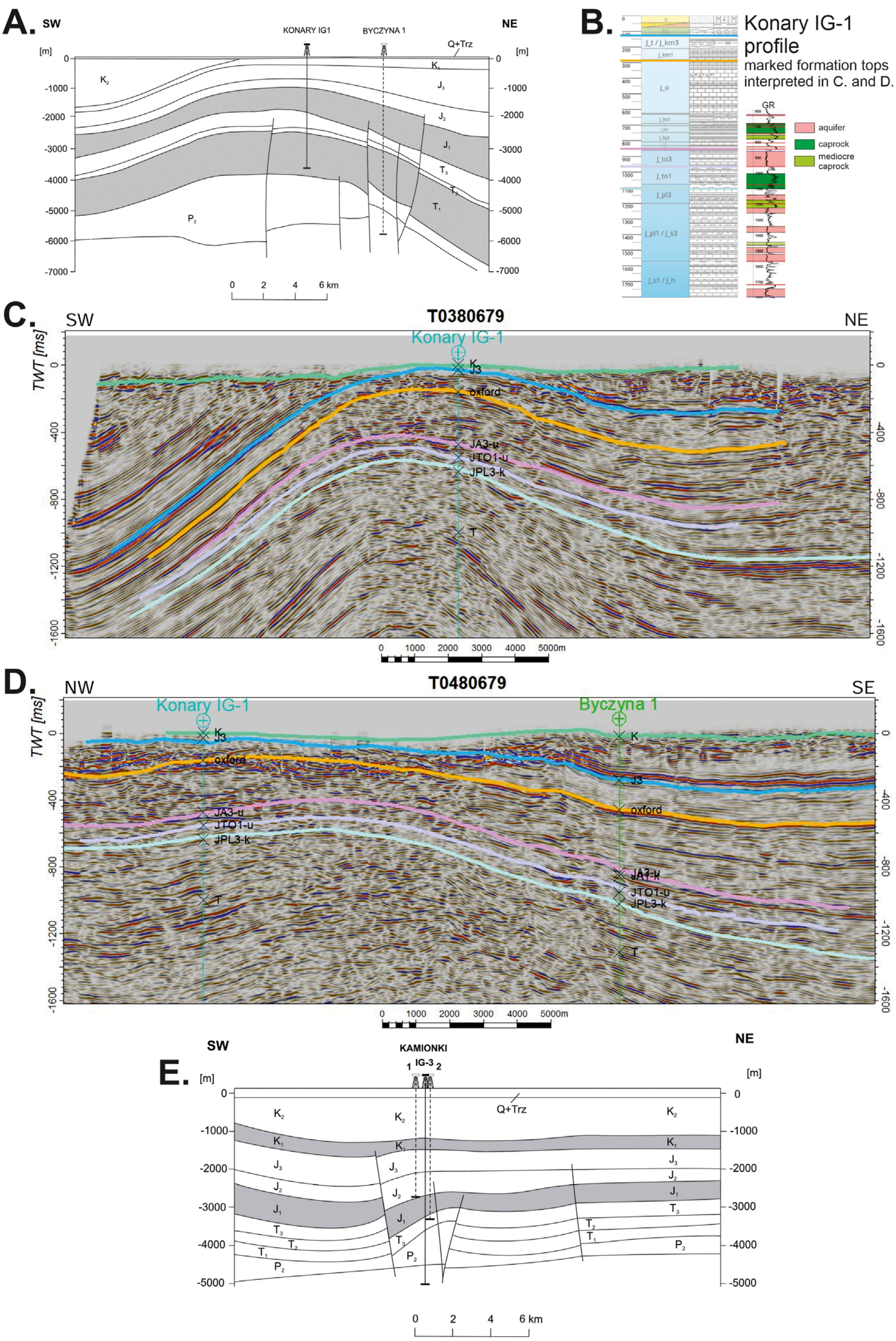

FIGURE 2
(A) A schematic geological section of the Konary structure (after Dziewińska et al., 2010). **(B)** The stratigraphic and lithologic profile of the Konary IG-1 borehole to the floor of Jurassic (Geoportal CBDG Boreholes, 2025b) and reservoir and caprock interpretation (Feldman-Olszewska, 2013). **(C,D)** Interpretation of seismic sections of the Konary structure (after Kijewska, 2024). The time range corresponds to a depth of 0–2,500 m below sea level. The terrain elevation is approximately 80–90 m above sea level. **(E)** A schematic geological section of the Kamionki structure (after Dziewińska et al., 2010).

TABLE 2 Storage options, relevant parameters and sensitivities. The parameters indicated in bold have been used in the Monte Carlo simulation.

Site/structure/area		Konary	Kamionki (K)	Kamionki (J)	Cambrian offshore PL	Reservoir and caprock indicators after Chadwick et al., 2008 *positive (cautionary)*
Reservoir(s)	Age and lithology (after literature)	Pliensbachian and Sinemurian sandstones	Lower Cretaceous sandstones	Lower Aalenian-Upper Toarcian sandstones	Middle Cambrian sandstones	
	Area [km^2] (uncertainty ±20% or 10%)	245 ± 50	77 ± 15	77 ± 15	5788 ± 600	
	Sensitivity	*The parameter influences storage volume. This is based on legacy seismic maps*	*The parameter influences storage volume. This is based on legacy seismic maps*	*The parameter influences storage volume. This is based on legacy seismic maps*	*The approximate area has satisfactory reservoir properties. The parameter influences the storage volume*	
	Cumulative thickness [m] (uncertainty - literature)	200 ± 50	170 ± 10	100 ± 70	52 ± 10	>50 m (<20 m)
	Sensitivity	*The parameter influences storage volume. This is based on available well data within and around the site*	*The parameter influences storage volume. This is based on available well data within and around the site*	*The parameter influences storage volume. This is based on available well data within and around the site*	*The parameter influences storage volume. This is based on available well data within the area*	
	Net-to-gross ratio [%] (uncertainty - literature)	80 ± 10	85 ± 5	85 ± 5	65 ± 10	
	Sensitivity	*The parameter influences storage volume. This is based on available well data within and around the site*	*The parameter influences storage volume. This is based on available well data within and around the site*	*The parameter influences storage volume. This is based on available well data within and around the site*	*The parameter influences storage volume. This is based on available well data within the area*	
	Effective porosity [%] (uncertainty - literature)	15 ± 5	20 ± 5	15 ± 5	11 ± 3	*>20% (<10%)*
	Sensitivity	*The parameter influences storage volume (and injectivity). This is based on analogs and available well data within and around the site*	*The parameter influences storage volume (and injectivity). This is based on analogs and available well data within and around the site*	*The parameter influences storage volume (and injectivity). This is based on analogs and available well data within and around the site*	*The parameter influences storage volume (and injectivity). This is based on available well data within and around the area*	
	Mean pressure [MPa] (uncertainty ±10% or based on regional aquifer depth range)	10.1 ± 1	14.1 ± 1.4	28.8 ± 2.9	18 ± 6	

(Continued on the following page)

TABLE 2 (*Continued*) Storage options, relevant parameters and sensitivities. The parameters indicated in bold have been used in the Monte Carlo simulation.

Site/structure/area		Konary	Kamionki (K)	Kamionki (J)	Cambrian offshore PL	Reservoir and caprock indicators after Chadwick et al., 2008 *positive (cautionary)*
Reservoir(s)	***Sensitivity***	*The parameter influences the assessment of CO_2 density. It is estimated to correspond to the hydrostatic pressure at the mean depth of the reservoir in the possible injection zone*	*The parameter influences the assessment of CO_2 density. It is estimated to correspond to the hydrostatic pressure at the mean depth of the reservoir in the possible injection zone*	*The parameter influences the assessment of CO_2 density. It is estimated to correspond to the hydrostatic pressure at the mean depth of the reservoir in the possible injection zone*	*The parameter influences the assessment of CO_2 density. It is estimated to correspond to the hydrostatic pressure at the mean depth of the reservoir in the possible injection zone*	
	Mean temperature [℃] (corresponding to the mean pressure uncertainty, actually to the relevant depth)	45 ± 4	44 ± 4	70 ± 7	68 ± 12	
	Sensitivity	*The parameter influences the assessment of CO_2 density. This is based on available well data within and around the site*	*The parameter influences the assessment of CO_2 density. This is based on available well data within and around the site*	*The parameter influences the assessment of CO_2 density. This is based on available well data within and around the site*	*The parameter influences the assessment of CO_2 density. This is based on available well data within and around the site*	
	CO_2 density [kg/m^3] https://www.peacesoftware.de/einigewerte/co2_e.html mean pressure and mean temperature input	511 ± 30	709 ± 15	776 ± 15	616 ± 98	
	Sensitivity	*The parameter influences storage capacity. This is based on mean pressure and temperature ranges*	*Based on mean pressure and temperature ranges, influences storage capacity*	*Based on mean pressure and temperature ranges, influences storage capacity*	*Based on mean pressure and temperature ranges, influences storage capacity*	
	Storage efficiency factor [%] (uncertainty – literature, or ±20% in case of regional aquifer)	13 ± 8	13 ± 8	13 ± 8	2 ± 0.4	
	Sensitivity	*The parameter greatly influences storage capacity. This is based on* Luboń (2021) *reservoir simulations*	*The parameter greatly influences storage capacity. This is based on* Luboń (2021) *reservoir simulations*	*The parameter greatly influences storage capacity. This is based on* Luboń (2021) *reservoir simulations*	*The parameter greatly influences storage capacity. This is based on* Vangkilde-Pedersen et al. (2009), *uncertainty ± 20%*	

(Continued on the following page)

TABLE 2 (*Continued*) Storage options, relevant parameters and sensitivities. The parameters indicated in bold have been used in the Monte Carlo simulation.

Site/structure/area		Konary	Kamionki (K)	Kamionki (J)	Cambrian offshore PL	Reservoir and caprock indicators after Chadwick et al., 2008 *positive (cautionary)*
Reservoir(s)	Representative permeability [mD] (after literature)	200–400	300–500	150–250	30–70	*>500 mD (<200 mD)*
	Sensitivity	*The parameter does not directly influence the volumetric storage capacity assessment, but it does affect the injectivity This is based on analogs and available well data within and around the site*	*The parameter does not directly influence the volumetric storage capacity assessment, but it does affect the injectivity This is based on analogs and available well data within and around the site*	*The parameter does not directly influence the volumetric storage capacity assessment, but it does affect the injectivity This is based on analogs and available well data within and around the site*	*The parameter does not directly influence the volumetric storage capacity assessment, but it does affect the injectivity This is based on available well data within and around the area, as well as analogs*	
Caprock(s)	Age and lithology (after literature)	Lower Toarcian claystones and mudstones	Upper Cretaceous marls and marly limestones	Bajocian and Upper Aalenian claystones	Silurian to Upper Cambrian claystones, shales and carbonates	
	Thickness [m] (after literature)	98–130	200–300	45–52	200–400	>100 m (<20 m)
	Sensitivity	*While the parameter does not directly affect volumetric storage capacity, it ensures safe storage if the caprock's quality and integrity are sufficient This is based on available well data within and around the site*	*While the parameter does not directly affect volumetric storage capacity, it likely ensures safe storage if the caprock's quality and integrity are sufficient This is based on available well data within and around the site*	*While the parameter does not directly affect volumetric storage capacity, it ensures safe storage if the caprock's quality and integrity are sufficient This is based on available well data within and around the site*	*While the parameter does not directly affect volumetric storage capacity, it ensures safe storage if the caprock's quality and integrity are sufficient This is based on available well data within the area*	
	Representative effective porosity [%] (after literature)	3–10	2–20	3–8	2–10	
	Sensitivity	*The parameter does not directly affect volumetric storage capacity This is based on analogs and available well data within and around the site*	*The parameter does not directly affect volumetric storage capacity This is based on analogs and available well data within and around the site*	*The parameter does not directly affect volumetric storage capacity. This is based on analogs and available well data within and around the site*	*The parameter does not directly affect volumetric storage capacity This is based on available well data within and around the area, as well as analogs*	
	Representative (matrix) permeability [μD] (after literature)	1–5	1-10 (and more)	1–5	0.06–0.17	

(Continued on the following page)

TABLE 2 (*Continued*) Storage options, relevant parameters and sensitivities. The parameters indicated in bold have been used in the Monte Carlo simulation.

Site/structure/area		Konary	Kamionki (K)	Kamionki (J)	Cambrian offshore PL	Reservoir and caprock indicators after Chadwick et al., 2008 *positive (cautionary)*
Caprock(s)	*Sensitivity*	*The parameter ensures safe storage provided the caprock is continuous and unbroken* *This is based on analogs*	*The parameter likely ensures safe storage provided the caprock is continuous and unbroken* *This is is based on analogs*	*The parameter ensures safe storage provided the caprock is continuous and unbroken* *This is based on analogs*	*The parameter ensures safe storage provided the caprock is continuous and unbroken* *This is based on available well data within and around the area, as well as analogs*	
	Secondary caprock (after literature)	Bajocian and Upper Aalenian, and Bathonian claystones and mudstones	-	as in Kamionki (K)	-	
Estimated volumetric (static) CO_2 storage capacity [Mt]: P10; P50; P90 Using Gnumeric software (Baudais et al., 2012) and the CSLF formula presented in Chapter 2. A normal distribution was assumed for all parameters except porosity, which was lognormal. The ranges correspond to ±3 standard deviations from the mean values		91; 230; 490	27; 121; 214	12; 59; 148	93; 159; 258	

CO_2 and the rock. The entire sequence is around 1,000 m thick, but the section above the Lower Cretaceous reservoir, which is 200–300 m thick and has a higher clay content, is assumed to provide an adequate seal. This may be the case if the sequence makes a continuous or composite confining system, as discussed by Bump et al. (2023).

No (digital) geological models of the structure or injection simulations have been carried out. The reservoir and caprock parameters presented in Table 2 were assumed similarly as in the case of Konary structure (after Wójcicki et al., 2014; Geoportal CBDG boreholes, 2025a; Feldman-Olszewska, 2013; Feldman-Olszewska et al., 2010; Feldman-Olszewska et al., 2012; Dziewińska et al., 2010; Ladage, 2016; Smulski et al., 2013). The same uncertainty range for the storage efficiency factor was therefore assumed as in the Konary structure. Similarly, a simple sensitivity analysis is included in Table 2. It shows that uncertainty in the storage efficiency factor has the greatest influence on the calculated volumetric storage capacity.

Monte Carlo simulations provided an assessment of the storage capacity of the Lower Cretaceous reservoir (Table 2) corresponding to the emissions of the nearby industrial installations (total: 4.328 Mtpa) over a period ranging from 6 to 49 years (median: 28 years). The Lower Aalenian-Upper Toarcian reservoir, which is located much deeper, has a storage capacity of approximately half that of the previous one.

3.2 Offshore CO_2 storage options

Approximately 120 km north of the Port of Gdańsk, there is an offshore Cambrian saline aquifer with likely satisfactory reservoir properties (Wójcicki and Pacześna, 2013; Gravaud et al., 2023), containing a couple of mature and relatively small hydrocarbon fields in the north-eastern part of the Polish sector of the Baltic Sea (see Figure 1). The aquifer is part of the mid-Baltic Dalders monocline, which extends from the Swedish to the Latvian sector. According to the international Bastor 2 project, the Dalders monocline could have a substantial volumetric storage capacity of up to 1.9 Gt (Nilsson, 2014; Vernon et al., 2013). However, it should be noted that this assessment may be overestimated if taking into consideration relatively low porosities and permeabilities of the relevant formations in Polish and adjacent Swedish sector of the Baltic Sea (Semyrka et al., 2010; Mortensen and Sopher, 2021). It is probable that the storage capacity of the Polish part will be inadequate to accommodate the emissions of all 16 selected emitters in the region. However, it may be sufficient for five of the northernmost emitters (Table 1; Figure 1; Wójcicki, 2025).

Should the regional Cambrian offshore aquifer in the Polish sector of the Baltic Sea be utilised as the storage site, it will be necessary to develop the necessary offshore infrastructure there, preferably integrated with the CO_2 terminal in the Port of Gdańsk. The CO_2 captured by the northernmost emitters could be transported to the prospective offshore aquifer in several ways. It could be transported by rail or by barge along the Vistula River, or it could be transported onshore via new pipelines to the future CO_2 terminal in the Port of Gdańsk (Table 1). The transportation of liquefied CO_2 from the Port of Gdańsk terminal to the offshore storage site under the Baltic Sea could be facilitated by ship or new undersea pipeline.

The reservoir rock of the aquifer is composed of Middle Cambrian sandstones, which are of mediocre to average porosity and permeability (Table 2). The reservoir is covered by a caprock made of a thick sequence of Upper Cambrian to Silurian claystones, shales and carbonates. The storage complex, which comprises the reservoir and the caprock, has been thoroughly explored in areas where hydrocarbon fields have been discovered and developed. However, little of this data has been published. The offshore Middle Cambrian saline aquifer is characterised in Table 2 using data and information from the following sources: Mortensen and Sopher (2021); Nilsson (2014); Semyrka et al. (2010); Vernon et al. (2013); and Wójcicki and Pacześna (2013). The area of the regional aquifer in the Polish sector that has satisfactory porosity and permeability is considered. The parameters of its Upper Cambrian–Silurian caprock are estimated using data from the following sources: Kuberska et al. (2021); Podhalańska et al. (2020); Poprawa (2020); and Schulz et al. (2021). It should be noted that, in the case of caprock permeability, data from analogs is assumed (Poprawa, 2020; Schulz et al., 2021). A simple sensitivity analysis is included.

According to the recently published results of CO_2 injection simulations into the aquifer (Wojnicki et al., 2023), its dynamic capacity is approximately 150 Mt. Monte Carlo simulations provided a similar assessment of the volumetric storage capacity of the Middle Cambrian reservoir (Table 2) corresponding to the emissions of the five northernmost industrial installations (total: 6.61 Mtpa) over a period of between 14 and 39 years (median: 24 years).

4 Discussion

There are many challenges to the development of the value chain, including regulatory, social, financial and technical issues.

4.1 The regulatory issues

Regulatory challenges include national regulations on onshore storage and transport, which are currently being drafted, as well as international regulations on offshore storage.

4.1.1 Onshore CO_2 storage

The regulations on onshore storage are to be announced soon for public consultations. The general legal framework of EU Directive 2009/31/EC on the geological storage of carbon dioxide (EUR-Lex, 2018) was adopted in Poland in 2013 and updated in 2023 as an amendment to the Geological and Mining Law (Galos, 2024). However, the law states that an ordinance issued by the permitting authority (i.e., the Ministry of Climate and the Environment) should determine the areas in which underground carbon dioxide storage complexes can be located. This means areas where potential CO_2 storage sites can be explored and characterised, and where storage permits can be applied for. The ordinance, issued in 2014 (The Ordinance, 2014), does not determine any onshore areas, only one offshore area. The permitting authority has recently completed an amendment to the ordinance including onshore areas, which is to be announced for public consultation soon. After these regulations are adopted, the exploration and characterisation of potential storage sites can begin. Then, applications for storage permits can be submitted (Galos, 2024). An application for a storage permit should include documentation on the characterisation and assessment of the potential storage complex and the surrounding area, as well as the monitoring plans. Polish regulations on these issues are consistent with Annexes I and II of EU Directive 2009/31/EC (EUR-Lex, 2018; Galos, 2024). The application also requires the full environmental impact assessment procedure, which may be the key hurdle.

4.1.2 Offshore CO_2 storage and the Helsinki Convention

Current national regulations permit the storage of CO_2 in the relevant part of the Baltic Sea (The Ordinance, 2014).

However, Article 11 of the Helsinki Convention recommends banning CO_2 storage under the Baltic Sea. CO_2 storage is classified as "dumping" under the 2014 Helsinki Convention (The Helsinki Convention, 2014), i.e., "the deliberate disposal at sea or into the seabed of waste or other matter from ships, other man-made structures at sea or aircraft," which is forbidden under Article 11. However, Article 11 already includes an exception for dumping. This issue could therefore be resolved through amending the article to create a new exception, as recommended by the relevant working groups of the Baltic Marine Environment Protection Commission (HELCOM) and subject to agreement by the relevant governments (Wammer Østgaard, 2024). The Call for tender: legal analysis of CCS in accordance with the Helsinki Convention was announced in September 2025 for this purpose (HELCOM, 2025). In parallel, the analysis of environmental and cumulative impacts and risks of Carbon Capture and Storage (CCS) in the Baltic Sea context is being conducted by the relevant working group (information from the author's personal communication with the national ministry). Both analyses are to be presented to the relevant government bodies of the Baltic Sea countries for decision by mid-2026.

4.2 Potential social acceptance barriers for onshore storage

The next important issue is therefore the acceptance of large-scale onshore underground storage by local communities, given the current lack of knowledge about carbon capture and storage (CCS) technology and the potential fear surrounding it. Over a decade ago, a large-scale CCS project involving the utilisation of an onshore saline aquifer structure, as well as a public awareness campaign, was developed in Poland (Bełchatów). However, it was subsequently cancelled, as were several other similar European projects at the time (ECA, 2018). In the EU research project SiteChar (Kaiser et al., 2013; Brunsting et al., 2015), local communities and authorities in areas where CO_2 storage in depleted gas fields is being considered were approached, interviewed, and informed about CCS technologies. The feedback was generally positive. In the research project Agastor (Wojakowski et al., 2024; Wojakowski et al., 2022) in area in NW Poland where CO_2 and natural gas storage in saline aquifer structures is being considered local communities and authorities were approached. The feedback was mixed. While negative attitudes were correlated with lack of knowledge about the technology, acceptance may increase if the benefits to the community are emphasized. A nationwide survey presented in a report by the NGO WiseEuropa (Giers, 2024) indicates that the general population has a low level of knowledge about CO_2 storage and that misinformation is prevalent in public opinion.

Therefore, the government, research institutions, and NGOs must be involved in disseminating knowledge about this topic again. Such an information and communication campaign must address several barriers (Giers, 2024). These include the relative lack of public knowledge about CO_2 storage and the visible benefits it could bring to local communities where it is developed. The well-known NIMBY (Not In My Back Yard) phenomenon is important and can be partly explained by misinformation in the mainstream and social media, or by honest information that is too technical and a low level of trust in state institutions and big industry. Another barrier is the lack of any large-scale CO_2 injection installations in operation in Poland. Currently, there is only one small-scale acid gas injection installation in a depleted gas field (Lubaś et al., 2020). There is a discrepancy between the high level of support for capturing CO_2 and the low level of support for storing it (except in areas where hydrocarbons are produced).

4.3 Financial issues

The ECO$_2$CEE Project of Common Interest, which is the seed part of the value chain, entails transporting carbon dioxide from two emitters (the Orlen Płock refinery and the Holcim cement plant) to the terminal in the Port of Gdańsk by rail until 2030. This is then followed by sea transport to storage sites beneath the North Sea (Orlen, 2024). The project is applying for European Union funding dedicated to infrastructure projects (European Commission, 2023) and must prevail in the competitive process. Construction of the industrial-scale capture unit at the Holcim cement plant is underway as part of the Go4ECOPlanet project. The project has received co-financing from the EU Innovation Fund for the full-chain solution (European Commission, 2022).

Following a review of potential locations for extending the ECO$_2$CEE PCI in Poland beyond 2030, it was proposed that emitters located between the Port of Gdańsk terminal and the two initial emitters could be considered. At the same time, it is proposed that the original PCI concept be supplemented and enhanced with additional transport and local storage options. It is recommended that new pipeline construction be prioritised as a more long-term solution, with the understanding that this may be more cost-effective than other options such as rail, barge or ship transport. According to Nooraiepour et al. (2025), the operational costs of transporting CO_2 by ship to the North Sea might be up to three times higher than by onshore pipeline (i.e. 30 vs 10 € per tonne).

4.4 Technical issues

One of the major risks to the further development of the value chain relates to the suitability of local storage options, a topic that this paper focuses on. Unlike hydrocarbon fields, the issue with saline aquifer structures is that the available legacy data is often insufficient or of poor quality for making investment decisions regarding the development of storage sites. Data on reservoir parameters is sparse and well-logging data calibrated with laboratory data is rarely available. There is usually even less data available on caprocks. Therefore, this study also used data on structures and formations in similar geological conditions - i.e., the same or equivalent formation and depositional environment, depth range, and diagenesis stage - to estimate the values and uncertainty ranges of the parameters in question. As shown in the case of one of the analysed structures, the quality of legacy seismic data may be insufficient for reliable assessment of caprock integrity.

Though these structures appear adequate for local storage in the value chain, according to this study based on limited and not always reliable data, their suitability, storage complex integrity, and storage capacity must be proven through exploration and site characterisation campaigns. This must be done using new models and injection simulations with new and legacy data that has been reprocessed and reinterpreted where necessary. Due to stakeholders' particular concern about the long-term integrity of the seal, this issue must be addressed in light of current global developments in this field. As highlighted in the IEAGHG (2024) report, the geomechanical characterisation of the storage complex should be conducted using well logging and laboratory analyses, as well as modelling of the geochemical processes related to CO_2-brine-rock interactions during and after injection. Ideally, coupled hydraulic, mechanical and chemical modelling should be used to evaluate the long-term integrity of the seal (IEAGHG, 2024). This generally aligns with the modelling requirements for the dynamic behaviour of CO_2 storage, as set out in Annex 1 of the EU Directive 2009/31/EC on the geological storage of carbon dioxide (EUR-Lex, 2018) and included in the relevant Polish legislation (Galos, 2024).

It should be noted that the scope of this study includes the harmonisation and validation of different data from the literature on the considered storage sites in saline aquifers, including previous domestic and European projects in this area. Table 3 presents the most important risks and knowledge gaps related to the evaluation of these sites and should be addressed at the appraisal stage. The results of this stage, which integrates new seismic surveys and boreholes with legacy data, will confirm or refute their suitability. If the results are positive, the next step is site characterisation, which, together with previously collected data, will provide the information necessary for applying for a storage permit.

4.5 The impact of these challenges on the feasibility of the value chain

The lack of onshore storage regulations in Poland is having a critical impact on the development of the value chain. The same applies to the Helsinki Convention's ban on offshore storage under the Baltic Sea. Exploration and characterisation of the potential onshore storage sites cannot begin until the relevant regulations

TABLE 3 Key risks and knowledge gaps pertaining to the evaluation of the considered storage options (based on Veloso, 2021).

Site/Attribute	Criteria	Konary	Kamionki (K)	Kamionki (J)	Cambrian offshore PL
Storage suitability	Capacity	Likely sufficient (volumetric, possibly dynamic)	Likely sufficient (volumetric)	Likely sufficient (volumetric)	Likely sufficient (volumetric and dynamic)
	Injectivity	Assumed in dynamic modeling	No data	No data	Assumed in dynamic modeling
Seal suitability	Seal	Likely good, to be verified (limited geochemical modeling of analogs available)	Likely good, to be verified (limited geochemical modeling of analogs available)	Likely good, to be verified (limited geochemical modeling of analogs available)	Likely quite good
	Fracture	No known fractures within the possible injection zone	No known fractures within the possible injection zone	No known fractures within the possible injection zone	No known fractures within the possible injection zone
	Wells	Legacy wells penetrating seal, no leakage documented	Legacy wells penetrating seal, no leakage documented	Legacy wells penetrating seal, no leakage documented	Legacy wells penetrating seal
	CO_2 density	High (supercritical)	High (supercritical)	High (supercritical)	High (supercritical)
	CO_2 migration	Vertical migration risk likely low, horizontal moderate	Vertical migration risk likely low, horizontal moderate	Vertical migration risk likely low, horizontal moderate	Vertical migration risk likely low, horizontal moderate
	Location	Close to other sinks and sources	Close to other sinks and sources	Close to other sinks and sources	Not far from future CO_2 terminal
	Monitoring	Suitable for performance monitoring	Suitable for performance monitoring	Suitable for performance monitoring	Suitable for performance monitoring
	Intervention	Possible remedial intervention	Possible remedial intervention	Possible remedial intervention	Possible remedial intervention
	Upside	Possibly a storage hub	Possibly a storage hub	Possibly a storage hub	Possibly a storage hub
Data quality	All criteria	2 legacy wells within the storage complex with well logging data and drilling cores, 20+ seismic lines, few reprocessed	3 legacy wells within the storage complex with well logging data and drilling cores, 20+ seismic lines	3 legacy wells within the storage complex with well logging data and drilling cores, 20+ seismic lines	Numerous legacy wells, 2D and 3D seismic, data mostly in the possession of a hydrocarbon company

have been implemented. Offshore storage permits cannot be granted until the ban on storage underneath the Baltic Sea is lifted. At this moment, the only feasible option is storage underneath the North Sea, provided the CO_2 terminal in Gdańsk is built.

Potential social acceptance barriers for onshore storage could not only prevent the granting of storage permits, but also the exploration and characterisation of potential storage sites. In order to increase public awareness, the government, research institutions and NGOs must collaborate on an information and communication campaign to address concerns related to CO_2 onshore storage among the general population and local communities. This has to be done before field works begin and storage permits are applied for. Otherwise, gaining social acceptance for onshore CO_2 storage could be problematic.

In terms of financial issues, it is important that the initial phase of the value chain, which includes the construction of two first industrial-scale capture installations (at the cement plant and the refinery) and CO_2 import and export terminal, relies on financial support from European Union programmes. The appraisal and characterisation of potential storage sites is not as expensive as the above-listed capital expenditures and is the responsibility of the interested stakeholders, who may also apply for EU funding. Further development of the value chain would require state aid. This includes the addition of capture units in other industrial installations and transport infrastructure, such as pipeline networks and hubs, as well as the possible enlargement of storage infrastructure. The relevant national strategies and legal framework are not yet ready.

To prove the suitability and safety of using local storage, site appraisal and characterisation are necessary. This applies both to potential onshore and offshore storage sites. Safe storage scenarios seem to be feasible at onshore sites, which enclose multi-layered reservoir and caprock sequences. However, the subsequent caprock evaluation and storage complex models may restrict the storage capacity that can be safely utilised. In such a case, additional structures located near the ones under consideration must be evaluated, appraised, characterised and developed. Offshore storage involves a regional saline aquifer, which is better explored than onshore structures, albeit unevenly. However, the storage capacity that can be safely utilised may be restricted by the caprock evaluation and storage complex modelling following the site characterisation.

5 Summary

In the CCUS ZEN project, one of the value chains under consideration included emission sources located in the region of northern Poland. The value chain is closely linked to the scope of the ECO_2CEE Project of Common Interest (PCI) on CO_2 import-export terminal in the Port of Gdańsk. In the initial phase of the ECO_2CEE project, the focus is on integrating railway transportation for CO_2 captured in two installations within the examined value chain. The carbon dioxide, once delivered to the terminal, will be transported by ship and stored beneath the North Sea. However, there is significant local storage potential within the region and its immediate vicinity, both onshore and offshore. It is therefore proposed that the original concept of the PCI be supplemented with additional CO_2 emitters of the value chain and enhanced by the introduction of additional transport and local storage options. The volumetric (static) capacities of the storage sites in the value chain are calculated taking into consideration available data on CO_2 injection simulations and caprock quality. Due to the limited legacy data available, information for structures in analogous geological conditions is also utilised to estimate the values and uncertainty ranges of the parameters in question. Although the estimated volumetric capacities seem adequate for the potential demand of the value chain, they should be verified using new field data, new geological models and injection simulations. The regulatory, social, financial and technical challenges, and their impact on the feasibility of the value chain, are discussed.

6 Conclusion

Utilising the local CO_2 storage options has the potential to expand the value chain of the ECO_2CEE Project of Common Interest in northern Poland beyond its original scope. In conjunction with the proposed transport infrastructure, onshore and/or offshore storage options in the region have the potential to supplement and enhance the original concept of the PCI, which is based on the CO_2 import-export terminal in the Port of Gdańsk.

The implementation of this solution is contingent on the completion of several key processes. Firstly, the adoption of national regulations on onshore CO_2 storage and transport is essential. Secondly, any potential barriers to the social acceptance of onshore CO_2 storage should be overcome. Thirdly, the issue of the ban on CO_2 storage under the Baltic Sea, as set out in Article 11 of the Helsinki Convention, needs to be resolved. Last but not least, funding for the initial phase and further development must be secured.

Although there is no published government-backed CCS roadmap for Poland yet, work on this is in progress. However, a couple of published documents address this issue, and their conclusions are consistent with the findings of this study on the use of CCS technologies for the decarbonisation of industrial installations and the utilisation of local CO_2 storage potential. Firstly, the policy and financing roadmap proposed by the NGO WiseEuropa (Laskowski and Giers, 2024) states that heavy industry sectors in Poland, such as cement, chemicals and steel, must use CCS technologies in order to fulfil the EU's decarbonisation goals and remain competitive in the market over the next few decades. They recommend developing long-term decarbonisation strategies and policies, facilitating state aid and completing the regulatory framework, as well as eliminating barriers and implementing financial mechanisms to support the deployment of CCS. Secondly, in its factsheet on prospects of CCS development in Poland, the Clean Energy Task Force (Busch et al., 2024) emphasises the need to utilise local CO_2 potential to decarbonise key industrial sectors. The rationale is that transporting all captured CO_2 to the North Sea for storage would make Polish industries less competitive due to high transport costs and the geographical distribution of emitters. The CATF also recommends using Polish onshore CO_2 storage potential to fulfil the needs of neighbouring countries.

As this paper does not focus on the feasibility of developing the value chain, but rather on the possibilities of utilising local CO_2 storage potential, a general roadmap for achieving this goal can be proposed. It should be noted that such activities do not constitute a research project, but could be the responsibility of interested stakeholders. Let us assume that the onshore storage regulations in Poland are adopted by the mid-2026 and that they cover the area in question. In this case, the stakeholder can prepare and submit to the permitting authority a geological work plan for seismic surveys (2D, then 3D) and appraisal well(s) drilling at the potential storage site (Galos, 2024). An environmental impact report approved by the relevant authority may be required, particularly if drilling is planned in a protected area. The drilling operation plan must be approved by the relevant mining authority. Before the work plan can be finalised, a detailed inventory of legacy seismic and well logging data, laboratory analyses and drilling cores must be compiled. This will inform the planning of new surveys, drilling and laboratory experiments on new and legacy core samples, as well as the reprocessing of legacy seismic data. It could take a couple of months to complete the work plan, and a similar amount of time could be required for approval by the permitting authority. Therefore, if no environmental impact report is required, fieldwork could begin by the end of 2026 at the earliest. In parallel, the reprocessing of selected legacy seismic lines should commence, as should laboratory analyses of the petrophysical and geomechanical parameters of the legacy reservoir and caprock samples. A geological-parametric model of the storage complex will then be constructed using new and legacy data, and any other relevant information. The site characterisation could take a couple of years (till 2028–2029). This includes dynamic modelling in the storage complex. Such characterisation is required when applying for the storage permit, along with monitoring plans and a full environmental impact assessment. The latter could also take a couple of years. According to the current Polish legal framework (Galos, 2024), pilot CO_2 injection is permitted during the site development phase, once a storage permit has been granted. Assuming the ban on

CO_2 storage under the Baltic Sea is resolved by mid-2026, a similar timeline and process could be adopted for offshore storage.

This study builds on the findings of the CCUS ZEN project by focusing on the local storage options of one of the value chains considered in that study (Lothe et al., 2025). The CCUS project used developments in CCUS around the relatively mature North Sea region as a model for developing new CCUS value chains in currently underdeveloped areas such as the Baltic Sea region. This study shows that deploying and developing such a relatively immature value chain requires integrating technical and non-technical aspects, including legal, social and policy frameworks. It focuses specifically on the use of local CO_2 storage potential as an alternative and supplementary measure to shipping, potentially forming part of future regional and pan-European CO_2 storage and CCS infrastructure.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AW: Writing – original draft, Writing – review and editing.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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