Geological CO_2 Storage in Poland: Review of Sequestration Potential, Policy Development, and Socio-Economic Factors

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Mohammad Nooraiepour[1*], Karol M. Dąbrowski[2], Mohammad Masoudi[1,3], Szymon Kuczyński[2], Zezhang Song[4], Ane Elisabet Lothe[3], and Helge Hellevang[1]

[1]Environmental Geosciences, Department of Geosciences, University of Oslo, P.O. Box 1047 Blindern, 0316 Oslo, Norway

[2]Faculty of Drilling, Oil and Gas, AGH University of Krakow, al. Mickiewicza 30, 30-059, Krakow, Poland

[3]SINTEF Industry, Applied Geoscience Department, 7465 Trondheim, Norway

[4]College of Geosciences, China University of Petroleum, Beijing, 102249, China

[*]Corresponding author: mohammad.nooraiepour@geo.uio.no

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Abstract

Poland's coal-reliant economy faces challenges in meeting European Union climate mandates. Carbon Capture and Storage (CCS) is pivotal for decarbonizing high-emission sectors enabling substantial CO_2 emission reductions while sustaining industrial competitiveness. This study conducts a geological CO_2 storage assessment in lower-maturity CCS regions, using Poland as a case study to evaluate sequestration capacity in areas with developing infrastructure and policy frameworks. This multidisciplinary review synthesizes scattered data and diverse subsurface resources to critically evaluate CO_2 storage potential, offering a structured assessment framework for global emerging CCS markets. It examines Poland's sequestration feasibility, integrating geological, regulatory, and socio-economic analyses to assess large-scale CCS deployment. Onshore saline aquifers alongside depleted hydrocarbon fields offer significant storage potential, with offshore Baltic Basin sites constrained by logistical and environmental regulations. Evolving policy and regulatory framework is evaluated, including recent amendments to the Geological and Mining Law that may facilitate onshore CO_2 storage near industrial hubs. We analyze regional and data compilation constraints, infrastructure readiness, and the integration of the CCUS value chain. Current storage assessments face challenges, including sparse data, restricted research access, and limited industry-academia collaboration, which impede maturing basin-scale and site-specific analyses to higher storage readiness levels. These gaps introduce significant uncertainty and undermine reliability, which limits informed business decisions. Socio-economic barriers, including public skepticism, financial uncertainties, and regulatory gaps, hinder large-scale CCS deployment. A framework for building public trust through transparent governance, inclusive community engagement, and proactive risk communication was suggested to build trust and foster CCS acceptance. By leveraging its geological assets and EU-aligned policies, Poland can spearhead CCS in Central and Eastern Europe, balancing energy security and climate goals.

Keywords: Carbon Capture and Storage (CCS), CO_2 Geological Storage, CO_2 Storage Potential, Saline Aquifers, Low-Carbon Transition, Public Engagement, Poland.

1 Introduction

Climate change is one of the defining challenges of our time, driven primarily by anthropogenic greenhouse gas emissions, most notably carbon dioxide (CO_2) [1]. These emissions contribute to rising global temperatures, erratic weather patterns, and significant disruptions to ecosystems worldwide [1, 2, 3, 4]. Scientific consensus underscores the urgent need to reduce these emissions, and in response, international and regional organizations have set ambitious targets to stabilize atmospheric CO_2 levels. Against this backdrop, technological solutions, particularly carbon capture and storage (CCS), have emerged as pivotal components of global decarbonization strategies [5, 6, 7].

Within this global framework, the European Union (EU) has taken a leading role in climate policy. Initiatives such as the European Green Deal [8, 9] and the Fit for 55 package [10, 11] highlight the EU's commitment to achieving climate neutrality by the mid-century, with a mandated 55% reduction in greenhouse gas emissions by 2030 compared to 1990 levels [12, 13]. These policies not only compel member states to adopt comprehensive decarbonization strategies but also promote the development and deployment of innovative technologies. In this context, CCS is recognized for its capacity to capture CO_2 from industrial sources and store it securely in geological formations, addressing emissions from sectors that are particularly difficult to decarbonize [14, 15, 16].

CCS technology operates by capturing CO_2 at its source, transporting it through pipelines, ships or other means, and injecting it into suitable geological reservoirs for long-term storage. This integrated approach fosters a cascade of technological developments, supports the expansion of critical infrastructure, and requires robust regulatory frameworks to ensure safe and effective CO_2 storage across Europe.

Poland presents a particularly compelling case study within this international and regional landscape [17, 16]. As one of the most carbon-intensive nations in Europe [18], Poland has historically relied on fossil fuels, especially coal, to drive its industrial development [19]. This longstanding reliance has resulted in large CO_2 emissions and a complex energy legacy [20]. However, the dual imperatives of meeting EU climate mandates and transitioning to a sustainable energy future have spurred significant shifts in the nation's environmental policies and energy strategies [21, 22].

A detailed examination of Poland's emission profile reveals an evolving energy landscape [23, 24]. Figure 1 shows the change in Poland CO_2 emission by source and sector from 2000 to 2022. Gradual decreases in total emissions and the fraction of total emissions from coal are observed. In 2000, coal represented 77 % of total CO_2 emission with a 221 Mt emission. However, in 2022 its share changed to 59 % with 165 MtCO_2. Emissions from oil have during the same time increased from 50 to 83 Mt CO_2 and natural gas from 18 to 31 Mt CO_2. CO_2 emission was mainly connected with electricity and heat production in Poland with a share of 49 % in 2022, and transport, which accounts for 23 % of the emission. Since 2020, emissions in the energy sector decreased from 163 Mt CO_2 to 140 Mt CO_2, while in transport the number increased from 27 Mt CO_2 to 67 Mt CO_2. Traditional coal-fired power plants and heavy industries, which once dominated the national energy landscape, are now gradually being replaced by an increasing share of renewable energy sources [25, 26, 27]. However, coal remains a central element of the energy mix, underscoring the urgent need to integrate CCS into Poland's broader decarbonization strategy [28, 29]. Fluctuations in emission trends over recent decades reflect the interplay of economic transitions, technological innovations, and policy reforms, resulting in a multifaceted set of challenges and opportunities [30, 31, 32].

Figure 2 shows that coal still accounts for 60 % of CO_2 emissions in electricity generation in 2023. However, total coal production gradually decreased from 137 TWh in 2000 to 100 TWh in 2023. During the same period, biofuel production increased from 0.2 to 8 TWh, and natural gas production increased from 0.9 to 17 TWh. Similarly, renewable energy production increased from 5 GWh in 2000 to 23 TWh for wind power and from 0 to 11 TWh for solar energy.

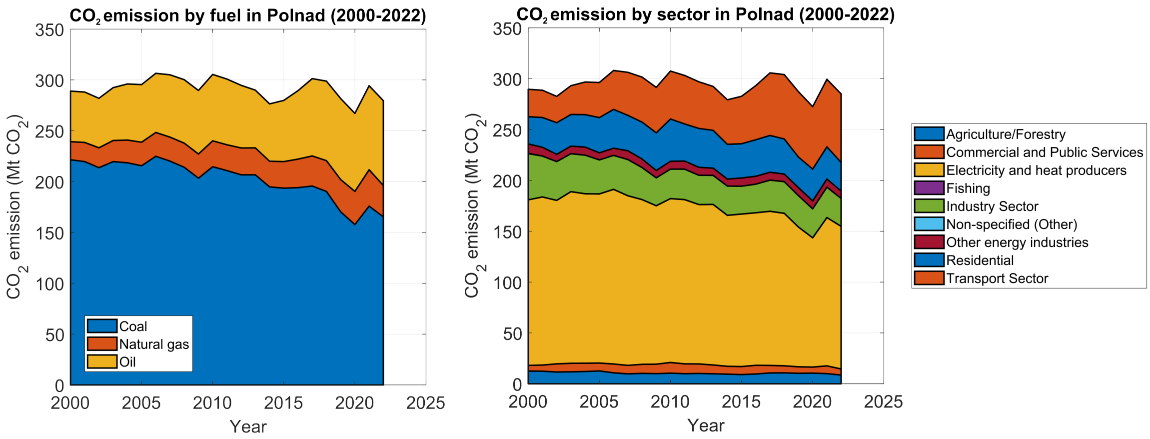

Figure 1: Energy-related CO_2 emissions in Poland from 2000 to 2022, categorized by (a) fuel type and (b) sector. (a) Emissions by fuel, dominated by coal (59% of total fuel combustion emissions in 2022), followed by oil and natural gas, reflecting Poland's heavy reliance on fossil fuels for power generation and industrial processes. (b) Emissions by sector, with electricity and heat production contributing the largest share (49% in 2022), followed by transport (24%), driven primarily by oil-based vehicles, and smaller contributions from industry and residential sectors. The data underscore Poland's coal-dependent energy system and the challenges of transitioning to low-carbon alternatives (data sourced from [33]).

The energy transition in Poland is further complicated by significant considerations of economic and energy security [22, 17]. The country's historical dependence on coal has provided a degree of economic stability and energy self-sufficiency, while also fostering entrenched infrastructural and social ties to the fossil fuel industry [34, 35]. The transition to a low-carbon economy, therefore, requires not only technological innovation but also profound economic restructuring and policy reform [16]. In this regard, CCS can emerge as a strategic enabler, offering a pathway to reduce CO_2 emissions while maintaining energy reliability and economic competitiveness [36].

Historically, CCS research and development in Poland have experienced both periods of intensive investigation and phases of stagnation, largely reflecting the broader political and economic transitions in the country [37, 38, 39, 16]. Early research initiatives focused on exploring the feasibility of CO_2 capture and geological storage were primarily academic in nature, laying the scientific foundation necessary for future applied projects [40, 41]. With the advent of EU funding and international collaborations, Polish CCS initiatives gained renewed momentum. Collaborative projects, pilot studies, and feasibility assessments have since emerged, reflecting a growing recognition of CCS as a critical component of the country's climate strategy [42]. These efforts have involved a variety of stakeholders, including government agencies, research institutions, and industrial players [43, 44].

As highlighted by the recent Norwegian-Polish CCS network initiative [16], a central aspect of this evolving narrative is the assessment of CO_2 storage options within Polish territory [45, 46]. Geological storage of CO_2 can be broadly categorized into onshore and offshore candidates, each presenting unique technical, economic, and environmental considerations [47]. In light of these considerations, it is imperative that Poland undertake a detailed assessment of its domestic and transboundary CO_2 storage options [48]. By leveraging advanced geological characterization techniques, simulation models, and risk assessment methodologies, Polish researchers and policymakers can develop a robust framework to evaluate the feasibility of various storage candidates [46, 47]. Such an integrated approach is essential not only to optimize the technical and economic performance of CCS projects but also to ensure that environmental and safety standards are rigorously maintained. Moreover, incorporating stakeholder perspectives, from local communities to industrial operators, will be critical in shaping a CCS strategy that is both socially acceptable and aligned with national and EU-level climate objectives [49, 48, 50].

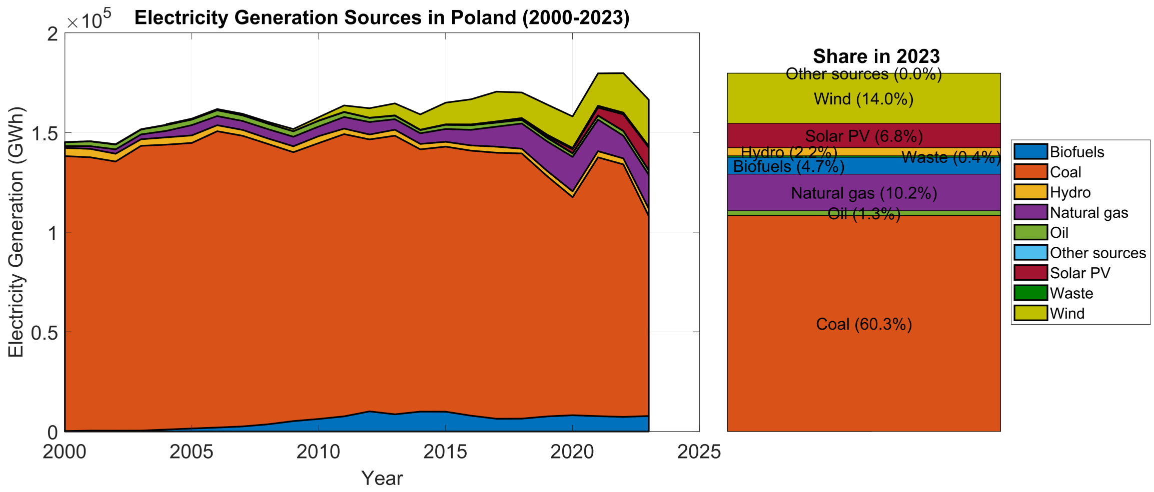

Figure 2: Electricity generation in Poland from 2000 to 2023 and its composition in 2023. (a) Trends in electricity generation, showing a historical reliance on coal, which peaked at 95% in 2000 but declined to 61% by 2023, alongside a rise in renewable sources (wind and solar) from 0% to 21% over the same period, driven by policy support and solar photovoltaic (PV) expansion. (b) Share of electricity generation in 2023, with coal (hard coal and lignite) contributing 61% (43% and 18%, respectively), onshore wind 14%, solar PV 9%, natural gas 8%, and smaller contributions from biomass (1%) and hydropower (1%). The data highlight Poland's coal-dominated energy mix, the rapid growth of renewables (27% of total generation in 2023), and ongoing challenges in achieving EU decarbonization targets (data sourced from [33]).

The potential for onshore CO_2 storage in Poland is supported by a growing body of geological data and research. Recent studies have highlighted the presence of several promising formations that could serve as secure reservoirs for long-term CO_2 sequestration. These include deep saline aquifers and depleted hydrocarbon fields that might exhibit the necessary characteristics for effective storage, such as high porosity, adequate permeability, and the presence of impermeable cap rocks. The development of detailed geological models, informed by seismic surveys, well logs, and other geophysical data, is crucial for identifying the optimal storage sites and assessing their performance under various operational dynamic injection scenarios [51].

On the offshore front, transporting CO_2 to North Sea storage sites has emerged as a focal point for CO_2 sequestration initiatives, driven by both its substantial storage capacity and proximity to major industrial regions in Europe. In the case of Poland, the possibility of shipping captured CO_2 to the North Sea presents both opportunities and challenges [16]. On one hand, leveraging the well-established storage infrastructure in the North Sea could accelerate the deployment of CCS, particularly in regions where onshore storage options are limited. On the other hand, the additional steps required, such as CO_2 purification and construction of long-distance pipelines, could impose significant financial and technical burdens. Furthermore, the cross-border nature of offshore storage necessitates a high degree of coordination among European countries, as well as the harmonization of regulatory standards and operational protocols [52, 53, 54].

In March 2025, Poland's ORLEN and Norway's Equinor signed a memorandum of understanding to jointly explore carbon storage opportunities in Poland [55]. This collaboration aims to identify potential CO_2 storage sites both onshore and in the Polish sector of the Baltic Sea [56, 57]. ORLEN has set a strategic goal to achieve an annual capacity of capturing, transporting, and storing 4 million metric tons of CO_2 by 2035, utilizing this capacity for its petrochemical and refining operations, with the remainder offered as a service to other industries [55, 57]. Equinor brings extensive experience in CCS, having initiated CO_2 storage in the offshore Sleipner field in 1996, and is involved in several large-scale CCS projects, including the Northern Lights project, the first cross-border CCS initiative providing CO_2 storage as a service [16].

The collaboration to explore carbon storage in the Baltic Sea may, however, face significant environmental, technical, and political challenges. The Baltic's shallow, brackish nature and ecological sensitivity raise concerns about potential leakage, which could acidify waters and disrupt hypoxic zones, harming marine life. The Helsinki Convention, governing Baltic environmental protection, creates legal ambiguity, as its prohibition on "dumping" might extend to CO_2 storage, unlike the more permissive London Protocol [58]. Competing offshore activities, such as shipping, fishing, and renewable energy, may further complicate site selection. The region's unique geology also demands the costly adaptation of proven North Sea storage techniques, from site-specific assessments to dedicated MMV, potentially straining the project's economic viability.

Geopolitical tensions, particularly with Russia, can add another layer of complexity. As a Helsinki Convention signatory with strategic interests in the Baltic, Russia could obstruct legal frameworks or view carbon sequestration infrastructure near Kaliningrad as a security threat, especially given recent incidents involving seabed infrastructure and strained NATO-Russia relations. Fossil fuel interests may also clash with CCS goals, reducing the prospects for cooperation. For the 4 million ton storage target by 2035 to succeed, these regional treaties must be navigated, along with securing EU support and mitigating regional influence, which could challenge, delay, or derail this climate initiative.

This study conducts a geological CO_2 storage assessment in lower-maturity CCS regions, using Poland as a case study to evaluate sequestration capacity and associated critical components like policy development and social acceptance parameters. It provides a multidisciplinary review of Poland's CO_2 storage potential, synthesizing scattered scientific research, industrial technical reports, and evolving regulatory framework to critically evaluate both onshore saline aquifers and depleted hydrocarbon fields, as well as offshore Baltic Basin sites. By addressing data scarcity, restricted research access, and limited industry-academia collaboration, the study develops a systematic methodology to assess sequestration capacity, offering a structured framework adaptable to global emerging CCS markets, including regions in Central and Eastern Europe, Southeast Asia, and parts of Africa.

This framework may serve as a blueprint for high-level assessments in lower-maturity CCS countries, outlining standardized storage assessment protocols and necessary ingredients to enhance large-scale CCS feasibility. The analysis explores geological characteristics, technical and economic feasibility, and key trade-offs that policymakers and industry stakeholders must navigate to formulate robust CCS/CCUS strategies. It addresses socio-economic barriers, including public skepticism and regulatory gaps, proposing strategies for transparent governance and inclusive community engagement to foster CCS acceptance. Positioned at the crossroads of Poland's coal-reliant economic tradition and environmental necessity, this study advances the understanding of geological sequestration, providing actionable insights for resilient and environmentally responsible strategies. Generalizing Poland's experience enriches the body of knowledge guiding CCS implementation across Europe and other emerging CCS markets, balancing energy security with climate goals.

2 Evolution of Policy and Regulatory Frameworks

The European Union (EU) has established a robust policy framework to combat climate change, promoting CCS/CCUS as critical technologies for decarbonization. The 2009 EU CCS Directive 2009/31/EC set standards for safe geological CO_2 storage, covering site selection, monitoring, and liability [59]. The 2018 Directive 2018/2001 on renewable energy supported synthetic fuels from captured CO_2, while the EU Emissions Trading System (ETS) Directive exempted permanently stored CO_2 from emission al-

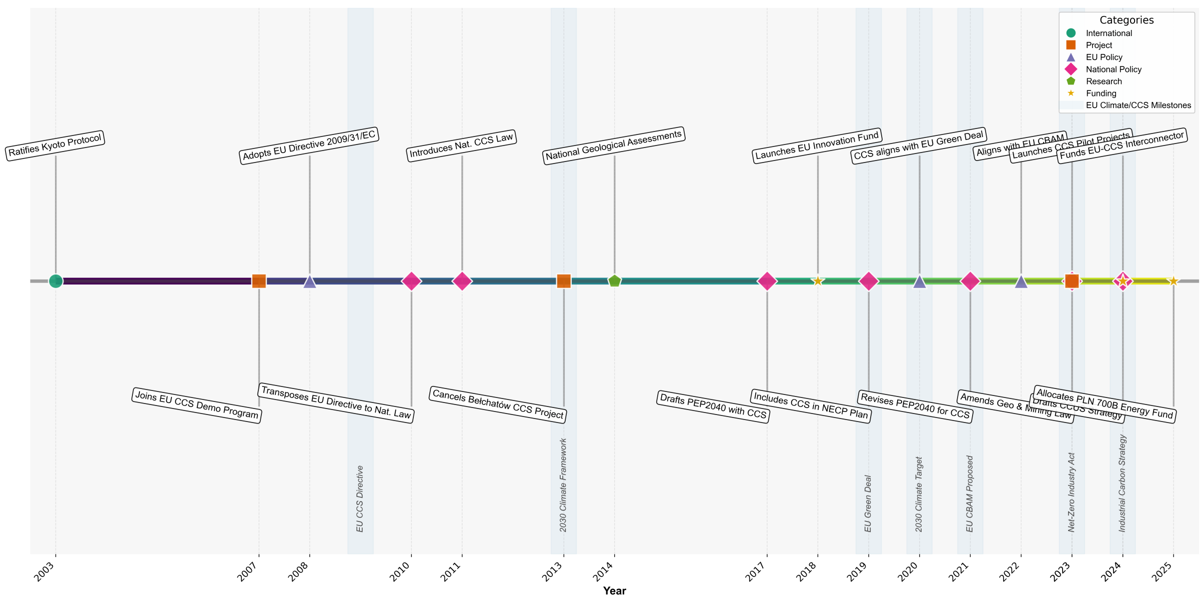

Figure 3: Timeline illustrating the evolution of Poland's CCS and CCUS policy and regulatory framework from 2003 to 2025, besides the progress of the EU regulatory framework. Key milestones include international agreements (e.g., Kyoto Protocol), EU policies (e.g., CCS Directive 2009/31/EC, EU Taxonomy, Net-Zero Industry Act, 2024 Guidance Documents), national legislation (e.g., 2011 CCS Act, NECP, PEP2040), projects (e.g., Bełchatów, Go4ECOPlanet, ORLEN–Equinor), research efforts, and funding (e.g., KPO, Energy Transformation Fund). EU climate and CCS directives, such as the EU Green Deal and Industrial Carbon Management Strategy, are depicted as shaded vertical bands. A gradient timeline underscores progression.

lowances [60]. The 2013 EU 2030 Climate and Energy Framework targeted a 20% emissions reduction by 2030 relative to 1990, encouraging CCS research [61]. The 2019 European Green Deal aimed for net-zero emissions by 2050, prioritizing CCS for hard-to-abate sectors like cement and steel [62]. The 2020 EU 2030 Climate Target Plan raised the emissions reduction goal to 55% by 2030, emphasizing industrial decarbonization [63].

The EU Taxonomy classifies CCS and CCU as significant contributors to climate change mitigation, enabling access to EU funding [64, 65]. The 2022 Corporate Sustainability Reporting Directive (CSRD) mandates environmental, social, and governance (ESG) reporting for large companies from 2024 and listed Small and medium enterprises from 2026, enhancing transparency for CCS/CCU investments [66, 67]. The 2021 Communication COM/2021/800 on sustainable carbon cycles set targets for absorbing 310 Mt CO_2eq via land and biomass and 5 Mt CO_2eq from industrial facilities by 2030 [68, 69]. In 2022, the EU proposed a voluntary carbon removal certification framework for industrial and biomass-based CO_2 removal, such as carbon farming [70, 71]. The 2021 Carbon Border Adjustment Mechanism (CBAM) incentivizes CCS in carbon-intensive sectors by imposing import carbon costs [72, 73]. The 2023 Net-Zero Industry Act (NZIA) designated CCS as a strategic technology, targeting 50 Mt CO_2 injection annually by 2030, streamlining permitting within 18 months, and mandating Member States to identify storage sites with private sector involvement, particularly from oil and gas [74, 75]. The 2024 EU Industrial Carbon Management Strategy projected 80 Mt storage by 2030, 300 Mt by 2040, and 550 Mt by 2050, requiring €12B and 7,500 km of CO_2 pipelines by 2030, and €16B and 19,000 km by 2040 [76, 77]. In July 2024, updated non-binding Guidance Documents for CCS permitting were released to harmonize licensing and attract investment [78, 79]. The EU Innovation Fund, launched in 2018, allocated €4.8B by 2024 for CCS/CCU projects [80, 81]. The EU ETS Phase IV (2021–2030) targets a 62% CO_2 reduction by 2030 compared to 2005, increasing carbon prices for high-emission industries [82].

Poland's CCS/CCUS framework has evolved over two decades, transitioning from legal foundations to practical strategies towards pilot and eventually large-scale projects in the years to come, driven by EU imperatives and national decarbonization goals. This evolution, marked by legal, strategic, funding, and project milestones, is illustrated in Figure 3.

2008–2014: Establishing Legal and Geological Foundations Poland's CCS/CCUS journey began with its 2003 ratification of the Kyoto Protocol, which emphasized innovative emission reduction technologies [83]. In 2007, Poland joined the EU CCS demonstration program, launching the Bełchatów CCS project for its largest coal plant, funded by the European Energy Programme for Recovery (EEPR). The project was abandoned in 2013 due to local opposition, economic concerns, and legal uncertainties over offshore storage [84, 85]. In 2008, the EU CCS Directive 2009/31/EC prompted Poland to transpose its provisions into national law by 2010 through amendments to the Geological and Mining Law [59]. The 2011 CCS Act clarified exploration and storage licensing procedures and introduced environmental impact assessment requirements. By 2014, geological surveys by the Polish Geological Institute and international partners estimated significant CO_2 storage capacity in deep saline aquifers and in the Baltic Sea basin, integrating CCS into the National Program for the Reduction of Greenhouse Gases [86, 87, 88]. These measures established the legal and geological foundation for CCS/CCUS development, but subsequent disruptions significantly hindered progress.

2015–2019: Planning and Initial Commitments Since 2015, Poland has attempted to embed CCS/CCUS gradually and slowly within its energy transition framework. The 2017 draft of the Polish Energy Policy until 2040 (PEP2040) identified CCS as a decarbonization tool for coal regions and heavy industry, aligning with its pillars of Just Transition, Zero-Emission Energy System, and Good Air Quality [89]. In 2019, the National Energy and Climate Plan (NECP) 2021–2030, prioritized research into CO_2 transport/storage and CCU pathways (e.g., CO_2-to-methane and methanol production) as part of the 2019 Strategic Directions for Energy Innovation Development, but deferred binding CCS deployment targets in favor of renewables and natural gas [90, 91]. Concurrently, Poland joined the Clean Energy for EU Islands Initiative, securing funding for feasibility studies to develop Baltic region CCS hubs [92, 93]. These initiatives marked Poland's initial commitment to CCS/CCUS, despite a primary focus on other energy sources.

2020–2025: Advancing National CCUS Strategy Since 2020, Poland has accelerated CCS/CCUS regulatory reforms, funding, and projects, aligning with EU climate goals while addressing its coal-dependent economy. In 2020, Poland adopted the EU Green Deal's 50 Mt CO_2 storage target by 2030 [62]. The 2021 PEP2040 emphasized CCS for coal region transformation, supported by a social agreement to develop CO_2 transport infrastructure and underground storage from 2023–2029. PEP2040 also linked CCS to low-carbon hydrogen production via steam methane reforming, supporting the 2021 Polish Hydrogen Strategy, and highlighted its role in electromobility and alternative fuels, including methanol production [94, 95]. Feasibility studies for CCS in cement, steel, and chemical industries began to emerge. In October 2023, amendments to the Geological and Mining Law and Energy Law lifted restrictions, enabling (at least in theory) industrial-scale CCUS deployment beyond demonstration projects. These amendments simplified licensing, exempted small installations ($<$100 kt CO_2 total storage), permitted direct CO_2 transport, and introduced CO_2-enhanced oil recovery (EOR) to enhance profitability. Investors were exempted from EU ETS emission allowances for captured and stored CO_2, reducing costs. The 2023 National Recovery and Resilience Plan (KPO) allocated €2.5B for CCS/CCU research and pilot projects [96, 97]. Moreover, the draft of the national CCUS strategy and the pilot concept of the Polish CCUS Cluster were materialized. The Energy Transformation Fund will support onshore and offshore further developments, aligning with Poland's EU Council Presidency, where CCS is positioned to influence EU policy [98, 99].

Key projects include the Go4ECOPlanet project (2023–2033), funded with €228M from the EU Innovation Fund (total cost €380M), targeting 100% CO_2 capture from the Kujawy cement plant, with liquefied CO_2 transported to North Sea storage sites. The ORLEN–Equinor Memorandum of Understanding (March 2025) aims for 4 Mt/year CO_2 storage by 2035 through joint assessment of onshore and Baltic Sea sites [55]. The Poland–EU CCS Interconnector, a project of common interest, received €2.5M from the Connecting Europe Facility in 2024 for feasibility studies. Additional financing comes from Horizon Europe, the European Bank for Reconstruction and Development (EBRD), and the European Investment Bank (EIB) [99, 100].

The cement industry, accounting for 3.8% of Poland's CO_2 emissions, faces pressure to adopt CCS due to the EU ETS phase-out of free CO_2 allowances by 2034, with reductions starting in 2026. The Kujawy CCS installation, planned for 2027, aims to capture 2.5 Mt CO_2 annually by 2030 and potentially 100% of emissions by 2040, though high costs (0.5–1.5B PLN per installation) remain a challenge.

3 Methodologies for Storage Capacity Assessments

This section outlines the scientific background and the methodologies used to evaluate Poland's CO_2 geological storage capacity, emphasizing its subsurface potential. It integrates regional geological data, static volumetric methods, and dynamic flow modeling, aligned with global frameworks such as the techno-economic resource-reserve pyramid [101, 102] and storage readiness level (SRL) [103]. Insights from key Polish subsurface projects, including the EU GeoCapacity initiative [104], CO_2STORE project [105], and EU CCUS ZEN [106], are incorporated to contextualize the findings.

3.1 Resource-Reserve Pyramid and Storage Capacity Tiers

The assessment of CO_2 storage capacity is structured within the techno-economic resource-reserve pyramid, a widely adopted framework in CCS research [101, 107, 102]. This hierarchical model, illustrated in Figure 4, categorizes storage potential into four progressive tiers, each imposing additional constraints to refine estimates from theoretical maxima to operationally viable capacities.

3.1.1 Theoretical Capacity

Theoretical capacity represents the upper physical limit of CO_2 storage, assuming all pore space within a geological formation is fully accessible for CO_2 storage (Fig. 4), either as a free phase or dissolved in formation fluids. It is calculated using a volumetric approach:

$$C_{\text{theo}} = A \times h \times \phi \times \rho_{\text{CO}_2} \times S_{\text{CO}_2}, \tag{1}$$

where A (m^2) is the formation area, h (m) is the gross thickness, ϕ (dimensionless) is the porosity, ρ_{CO_2} (kg/m^3) is the CO_2 density at reservoir conditions, and S_{CO_2} (dimensionless) is a storage efficiency factor reflecting total pore accessibility. For saline aquifers, S_{CO_2} may approach unity in idealized scenarios, while in hydrocarbon reservoirs, it is constrained by original fluid volumes [108].

Theoretical estimates in Polish assessments rely on broad geological mapping but lack site-specific refinement. Assumptions include uniform porosity and full accessibility, which yield overly optimistic estimates but overlook geological complexities.

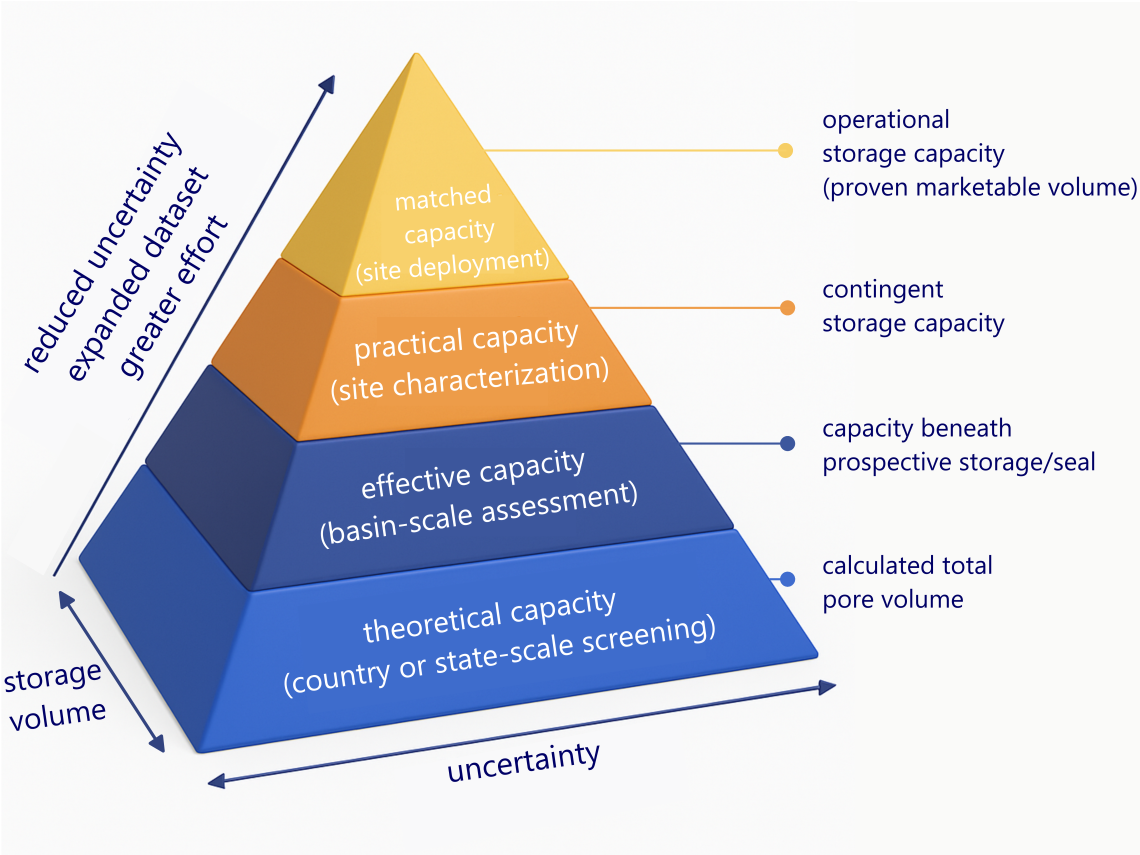

Figure 4: Techno-economic pyramid of CO_2 storage capacity, from theoretical (maximum geological potential) to effective (basin-scale sites screened for geological suitability), practical (sites with detailed characterization and infrastructure), and matched (operationally proven, market-ready storage volumes). It illustrates how uncertainty, storage volume estimates, data requirements, and effort increase toward higher tiers.

3.1.2 Effective Capacity

Effective capacity refines theoretical capacity by applying geological and engineering constraints, such as depth, salinity, porosity-permeability cutoffs, and formation heterogeneity. It is a subset of theoretical capacity, adjusted via efficiency factors (E_{saline} for aquifers, $E_{\text{hydrocarbon}}$ for depleted reservoirs) that account for irreducible water saturation, pressure limits, and injectivity. The formulation for saline aquifers, adapted from USDOE methodologies [108], is:

$$C_{\text{eff}} = A \times h_g \times \phi \times N_{TG} \times \rho_{\text{CO}_2} \times E_{\text{saline}}, \tag{2}$$

where h_g (m) is the gross thickness, N_{TG} (dimensionless) is the net-to-gross ratio, and E_{saline} (typically 1–20%) reflects usable pore volume and displacement efficiency.

For hydrocarbon reservoirs, effective capacity leverages displaced hydrocarbon volumes [107]:

$$C_{\text{eff, oil}} = C_e \times \rho_{\text{CO}_2} \times RF \times OOIP \times B_f - (V_{iw} - V_{pw}), \tag{3}$$

$$C_{\text{eff, gas}} = C_e \times \rho_{\text{CO}_2} \times RF \times OGIP \times \left(\frac{p_{\text{res}} T_{\text{sc}} Z_{\text{sc}}}{p_{\text{sc}} T_{\text{res}} Z_{\text{res}}} \right), \tag{4}$$

where RF is the recovery factor, $OOIP$ and $OGIP$ are original oil and gas in place, B_f is the formation volume factor, and V_{iw}, V_{pw} are injected/produced water volumes (often omitted due to data scarcity).

C_e (e.g., 0.25–0.48 for oil, 0.63–0.87 for gas) adjusts for mobility and aquifer effects [107].

3.1.3 Practical Capacity

Practical capacity narrows effective capacity by incorporating technical, economic, and regulatory constraints, such as infrastructure availability, injection costs, and legal frameworks. It requires operational data from pilot projects, which remain limited in Poland post-Bełchatów's cancellation [16]. Estimates decrease significantly at this stage due to site-specific challenges (Fig. 4), such as legacy well integrity and restrictions in the Baltic Sea, as mentioned in the Introduction. Limited pilot data significantly restricts Poland's practical capacity estimates.

3.1.4 Matched Capacity

Matched capacity aligns CO_2 sources (e.g., industrial emitters) with storage sites, optimizing injectivity, capacity, and proximity. Poland's ORLEN-Equinor collaboration (2025) may ultimately demonstrate this stage, though detailed assessments remain pending or confidential, awaiting future realization.

3.2 Storage Readiness Level (SRL)

The Storage Readiness Level (SRL) framework is a standardized tool designed to assess the maturity of geological sites for CO_2 storage [103]. Inspired by the Technology Readiness Level (TRL) system, SRLs adapt this concept to evaluate the progression of a storage site from initial identification to operational readiness, encompassing technical, regulatory, and operational milestones. Developed through collaborative research and industry experience in the UK, Norway, and the Netherlands since the 1990s, the SRL framework, as shown in Figure 5, offers a nine-level scale to communicate site maturity to stakeholders, including policymakers, investors, and the public. By addressing key aspects such as geological characterization, regulatory compliance, and infrastructure planning, SRLs enable a systematic comparison of sites across diverse geological and regulatory contexts, facilitating informed decision-making for CCS project development [103].

Figure 5 shows that the SRL framework is derived by integrating three core pillars: technical appraisal, permitting, and operational planning. Each level requires specific evidence to justify progression. Technical appraisal involves detailed geological studies, including seismic surveys, well data analysis, and reservoir modeling, to estimate storage capacity and ensure containment integrity through mechanisms such as structural trapping and residual trapping. Permitting evaluates compliance with national and international regulations, such as the EU CCS Directive, which mandates environmental impact assessments and public engagement. Operational planning addresses logistical requirements, including CO_2 transport infrastructure and monitoring systems for long-term site management. As Figure 5 outlines, the SRL scale ranges from SRL 1 (conceptual site identification) to SRL 9 (fully operational storage site), with intermediate levels marking milestones like feasibility studies (SRL 4–6) and pilot injections (SRL 7–8). Applied to hundreds of sites, including 742 offshore formations in the North Sea, the framework accommodates site-specific challenges and regulatory variations, supporting the global scaling of CCS by prioritizing sites with high readiness and reducing uncertainties in storage capacity and safety [103, 106].

The Storage Readiness Level (SRL) framework expands on the techno-economic resource-reserve pyramid assessment (Fig. 4) and provides critical indicators for evaluating the suitability of geological sites for CO_2 storage, guiding the progression from initial assessment to operational deployment (Fig. 5). SRL 1 involves a preliminary, state- or country-scale assessment to estimate theoretical storage capacity and identify geological characteristics conducive to CO_2 storage, such as suitable lithology and

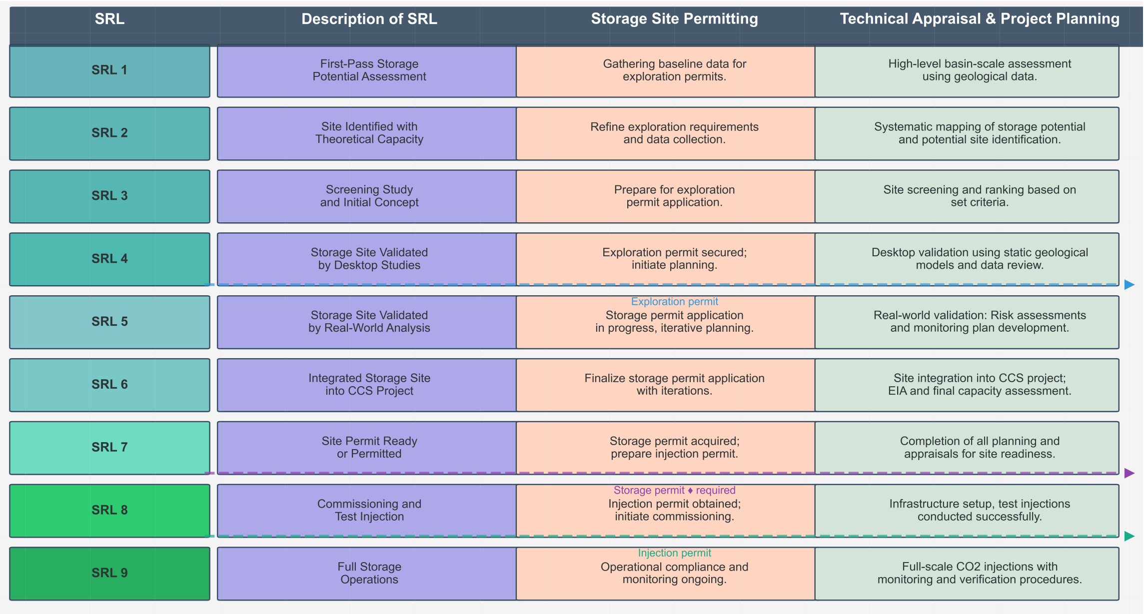

Figure 5: Illustration of the Storage Readiness Level (SRL) framework for CO_2 storage site evaluation, detailing the progression from SRL 1 to SRL 9. Each level includes descriptions of technical appraisal, permitting requirements, and project planning milestones, with color-coded stages and permit timelines indicating key regulatory steps.

structural traps. At SRL 2, sites with theoretical capacity are systematically mapped, with assessments based on geological data and theoretical calculations of storage potential, laying the groundwork for more targeted evaluations. SRL 3 advances to a detailed screening study, focusing on individual storage sites and developing an initial project concept by integrating geological, technical, economic, and geographical criteria (Fig. 5). This stage involves selecting candidate sites for further characterization and feasibility studies, marking a transition from broad exploration to site-specific planning [103]. The EU-funded CCUS ZEN project recently reevaluated prior assessments of Polish subsurface storage potential [86] and classified a list of identified CO_2 storage sites in Poland at SRL 2–3, indicating early-stage geological and technical suitability [106].

3.3 Assessment Framework for Storage Potential

In the context of CO_2 geological storage, a prospect unit is a critical classification for identifying and developing viable storage sites, encompassing several key geological and technical concepts. Reservoir formations, characterized by favorable reservoir properties such as high porosity and permeability, form the foundation for effective CO_2 storage, ensuring long-term retention of carbon dioxide. Within these formations, storage units are defined as coherent, mappable subsurface bodies of reservoir rock located at sufficient depths, sharing similar geological characteristics that enable secure CO_2 containment with minimal leakage risk. Daughter units, which are specific structural and stratigraphic traps within a storage unit, include depleted hydrocarbon fields that leverage their established geological structures for safe storage. A prospect unit, the most refined classification, is a daughter unit evaluated as commercially viable and bankable for CO_2 storage, marking its potential for development in CCS projects.

3.3.1 Reservoir Characterization and Static Modeling

High-resolution 3D geological models are foundational for static CO_2 storage capacity estimation, integrating well logs, core samples, 3D seismic surveys, and other geophysical measurements. These models delineate reservoir geometry and quantify petrophysical properties (e.g., porosity, permeability, and fluid saturation) that are essential for static and dynamic simulations. Advanced workflows employ seismic inversion and geostatistical techniques to enhance model fidelity. Static capacity is calculated volumetrically:

$$V_{CO_2} = A \times h \times \phi \times \rho_{CO_2} \times E, \tag{5}$$

where A (m^2) is the effective area, h (m) is the net thickness, ϕ (dimensionless) is the porosity, ρ_{CO_2} (kg/m^3) is the supercritical CO_2 density, and E (dimensionless) is an efficiency factor (e.g., 1–20% for aquifers, 50–80% for depleted reservoirs) accounting for sweep efficiency, heterogeneity, and trapping mechanisms [109]. Sensitivity analyses, using Monte Carlo simulations with triangular distributions (P10, P50, P90), can refine further uncertainty bounds.

3.3.2 Dynamic Flow Modeling

Dynamic flow modeling simulates CO_2 injection behavior, integrating multiphase fluid dynamics, mass transport, and geomechanical interactions. Governed by conservation laws, these models predict plume migration, pressure evolution, and caprock integrity, which are critical for operational planning and risk management. The core equations are:

$$\text{Mass Conservation (Multiphase Flow):} \quad \frac{\partial}{\partial t}(\phi \rho S) + \nabla \cdot (\rho \mathbf{v}) = Q, \tag{6}$$

$$\text{Momentum Conservation (Darcy's Law):} \quad \mathbf{v}_\alpha = -\frac{k k_{r\alpha}}{\mu_\alpha}(\nabla p_\alpha - \rho_\alpha \mathbf{g}), \tag{7}$$

$$\text{Energy Conservation (Heat Transport):} \quad \rho c_p \frac{\partial T}{\partial t} + \nabla \cdot (-k_T \nabla T) = H_{\text{source}}, \tag{8}$$

where $\mathbf{v}_\alpha$ (m/s) is the Darcy velocity of phase α, k (m^2) is absolute permeability, $k_{r\alpha}$ (dimensionless) is relative permeability, μ_α ($Pa \cdot s$) and ρ (kg/m^3) are viscosity and density, ϕ (dimensionless) is porosity, S (dimensionless) is saturation, Q ($kg/m^3/s$) is a source/sink term, $\mathbf{g}$ (m/s^2) is gravitational acceleration, c_p ($J/kg \cdot K$) is heat capacity, k_T ($W/m \cdot K$) is thermal conductivity, and H_{source} is a heat source term.

3.3.3 Risk-Weighted Capacity and Uncertainty Analysis

A risk-weighted approach bridges static and dynamic assessments, adjusting dynamic capacity (C_{dyn}) with geological and operational risks:

$$C_{\text{eff}} = C_{\text{dyn}} \prod_{i=1}^{n} (1 - R_i), \tag{9}$$

where R_i represents risks (e.g., fault reactivation, well leakage, maximum allowable pressure), quantified via techniques such as probabilistic and Monte Carlo-type methods. An integrated framework could also employ multi-criteria decision analysis (MCDA), balancing technical feasibility, economic viability, and environmental safety.

3.4 Data Compilation and Regional Constraints

The evaluation of CO_2 storage potential in Poland, as exemplified in Figure 6, hinges on integrating diverse datasets and local geological considerations. However, current assessments face significant challenges rooted in the lack of availability and comprehensiveness of data, which are compounded by limited access to the research sector and collaborative industry-academia R&D initiatives that could maximize the utility of existing sources. Consequently, basin-scale assessments and site-specific studies must account for confidence intervals and reliability caveats until new seismic surveys, well-site measurements, and core data become available. We emphasize to stakeholders that the current state of knowledge for identified storage candidates and their tentative high-level storage capacity estimates, such as those presented in Table 2, is still insufficient for making definitive business decisions, necessitating further scrutiny and validation.

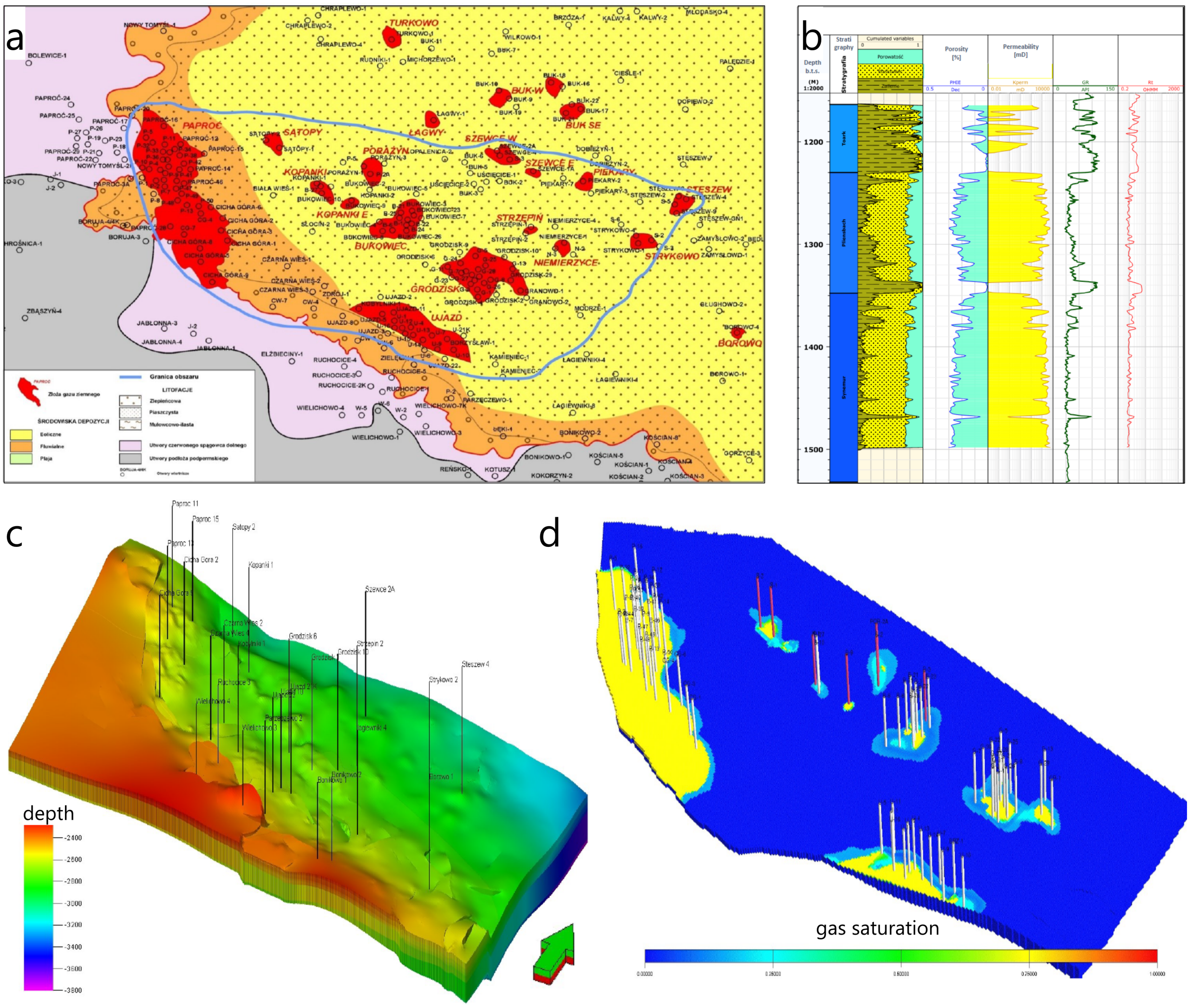

Figure 6: Multiscale analysis of the Poznań trough (northern Fore-Sudetic Monocline, FSM): (a) geological map with study area borders; (b) petrophysical interpretation of Rotliegend reservoir (lithology, shaliness, porosity, permeability); (c) 3D subsurface model color-coded by depth; (d) CO_2 injection simulation (11–25 million tons, 3–7 wells) in structural highs, color-coded by gas saturation, showing secure storage beneath Zechstein caprock. (modified from [86])

Geological Data: Subsurface characterization relies on core samples, geophysical well logs, and seismic surveys (Fig. 6). In Poland, it is often sourced from the Polish Geological Institute (PGI-NRI), Polskie Górnictwo Naftowe i Gazownictwo (PGNiG), and Grupa LOTOS. These datasets, to their extent, provide input into reservoir properties across Poland's sedimentary basins. Legacy Soviet-era 2D seismic data (1970s–1980s) that has been reprocessed with modern algorithms supplements contemporary 3D surveys. However, its coarse resolution limits detailed modeling of structural traps and reservoir heterogeneity. Recent efforts to digitize and reinterpret this data have improved coverage, but gaps still persist in the majority of regions, particularly regarding the characterization of deep saline aquifers.

Hydrogeological Data: The Poland Hydrogeological Atlas [110, 111] provides preliminary salinity data (typically >10,000 mg/L for viable aquifers) and pressure gradients, essential for assessing CO_2 solubility, plume migration, and injectivity. Over-pressured formations are excluded in many relevant studies, which is consistent with global practices aimed at mitigating injection challenges and ensuring operational feasibility when accurate information is absent.

Thermodynamic Data: Geothermal gradients, often ranging from 25–35°C/km, dictate CO_2 phase behavior (supercritical above 31°C and 73.8 bar) and influence storage efficiency at varying depths. These data, combined with pressure-temperature profiles from well logs (where available), enable computation of CO_2 density and viscosity under reservoir conditions, aligning with international standards [108].

Reprocessed Soviet-era 2D seismic data, despite modern enhancements, falls short of the resolution required for detailed fault mapping and dynamic simulations. In the Polish Lowland Basin (PLB), over 1,200 legacy wells, many of which were drilled before the 1980s, exhibit uncertain cement integrity. This necessitates the use of cement evaluation logs and pressure tests to quantify leakage risks. Recent studies estimate that 20–40% may require remedial sealing, a concern echoed in global CCS assessments [112, 113].

As detailed in subsequent sections, many study areas (e.g., Region V in Podlasie, Figure 8) face geological and geophysical data scarcity, including limited 3D seismic coverage and reliance on 2D surveys. The Baltic Sea analogs suggest a speculative theoretical capacity of 1.0 Gt. Similarly, Study Area VIII's 1.64 Gt estimate, derived from Swedish Cambrian reservoirs, is limited by sparse well penetrations beyond the B3 oil field [86]. These extrapolations exhibit wide confidence intervals (P10–P90 ranges of ±30–50%) due to insufficient subsurface validation.

Current basin-scale and prospect-specific studies must thus incorporate probabilistic uncertainty analyses (e.g., Monte Carlo simulations) to define reliability bounds. Until adequate 3D seismic surveys, modern well logs, and core analyses are acquired, capacity estimates and mandatory coupled THMC assessments remain provisional. It underscores the need for targeted exploration campaigns and enhanced industry-academia collaboration to bridge knowledge gaps and refine Poland's CCS roadmap with site-specific characterizations.

4 Geological Setting and Sedimentary Basins in Poland

Poland's subsurface represents a geological mosaic shaped by a dynamic tectonic history and multifaceted stratigraphic developments. This complexity reflects a geological evolution impacted by significant tectonic epochs, glacial phenomena, and sedimentary dynamics. The lithostratigraphic framework of the region emerges as a palimpsest of Phanerozoic sedimentation, profoundly influenced by the Caledonian, Variscan, and Alpine orogenic cycles, as well as by subsequent post-orogenic subsidence and glacial overprinting [114, 115, 116]. Each orogenic event contributed distinct structural characteristics and sedimentary sequences, which have collectively fashioned a diverse array of sedimentary basins across the region, varying significantly in age, lithology, structural composition, and petrophysical properties, all of which hold implications for CO_2 storage endeavors [117]. Figure 7 shows the geological and geomorphological overview of Poland and its tectonic framework.

4.1 Tectonic Evolution

Caledonian Orogeny

The Caledonian progeny (Fig. 7a) , an early Paleozoic tectonic event, was critical in forming Poland's foundational geological structures. During this period, the closure of the Tornquist Sea led to dramatic

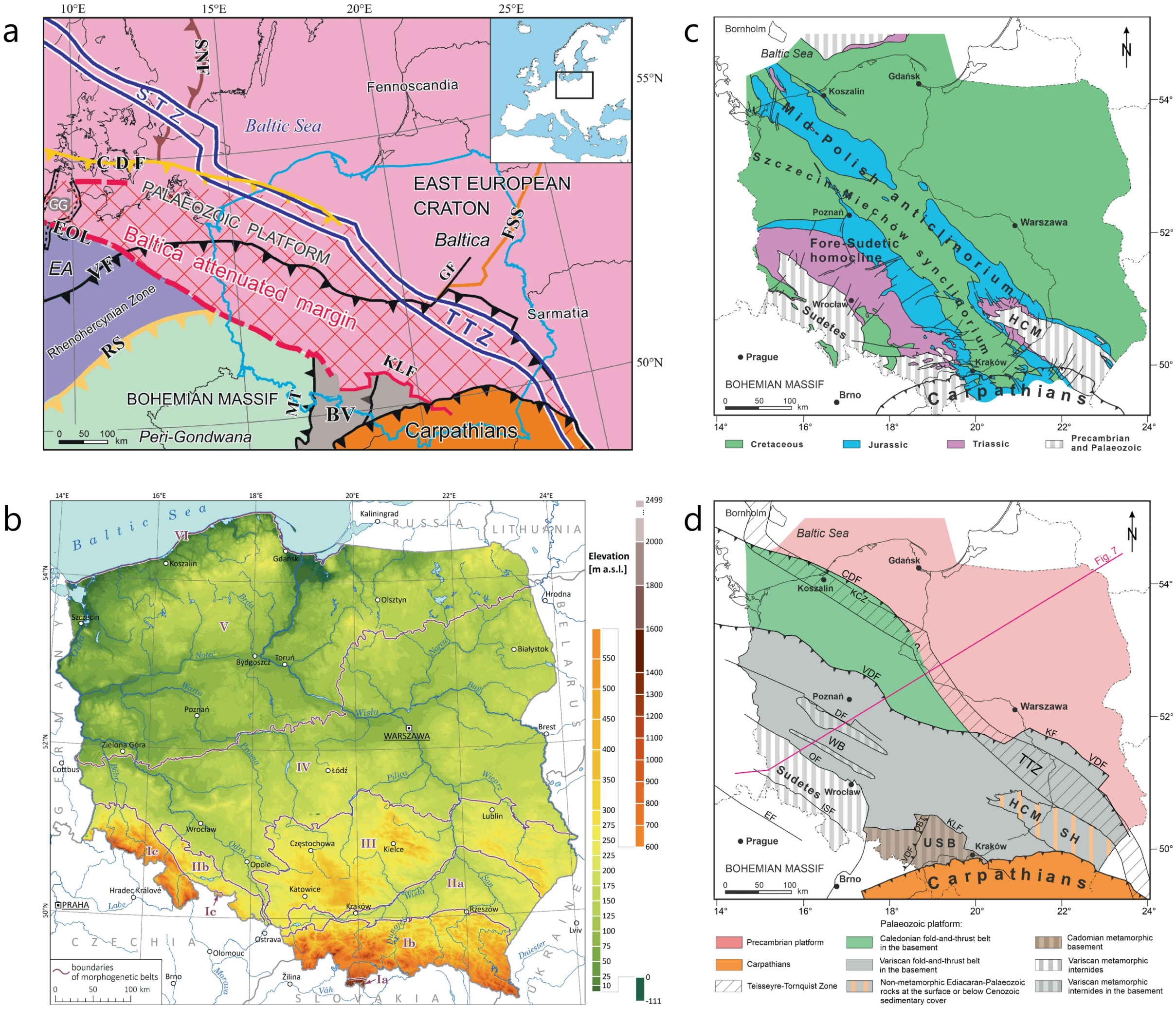

Figure 7: Geological and geomorphological overview of Poland and its tectonic framework. (a) Crustal domains at the transition from the Precambrian East European Platform to the Palaeozoic Western European Platform and Western Carpathians, with major structural elements and the Polish boundary (blue outline). Inset map shows the location within Europe. Abbreviations: BV—Brunovistulicum; CDF—Caledonian Deformation Front; EA—East Avalonia; EOL—Elbe–Odra Lineament; FSS—Fennoscandia-Sarmatia Suture; GF—Grójec Fault; GG—Glückstadt Graben; KLF—Kraków–Lubliniec Fault; MT—Moldanubian Thrust; RS—Rheic Suture; SNF—Sveconorwegian Front; STZ—Sorgenfrei–Tornquist Zone; TTZ—Teisseyre–Tornquist Zone; VDF—Variscan Deformation Front (modified from [118, 119]). (b) Altitudinal diversity of Poland with morphogenetic belts. Mountains: Ia—High Mountains (Tatra Mts.); Ib—Medium–High Mountains of the Alpine System (Beskidy Mts.); Ic—Medium–High Mountains of the Variscan System (Sudetes). Fore-mountain areas: IIa—Sub-Carpathian Basins; IIb—Sudetic Foreland. III—Uplands; IV—Old Glacial Relief (Central Poland); V—Young Glacial Relief (Northern Poland); VI—Coastal Zone (modified from [120]). (c) Pre-Cenozoic geology of Poland, highlighting the Permian–Mesozoic Polish Basin structure during Late Cretaceous inversion. HCM—Holy Cross Mountains (modified from [121, 118]). (d) Tectonic provinces of Poland, excluding Permian–Cenozoic cover. Abbreviations: CDF—Caledonian Deformation Front; DF—Dolsk Fault; EF—Elbe Fault; HCM—Holy Cross Mountains; ISF—Intra-Sudetic Fault; KCZ—Koszalin–Chojnice Zone; KF—Kock Fault; KLF—Kraków–Lubliniec Fault; OBT—Orlová–Boguszowice Thrust; OF—Odra Fault; SH—San Horst; TTZ—Teisseyre–Tornquist Zone; USB—Upper Silesia Block; VDF—Variscan Deformation Front; WB—Wolsztyn Block [122, 118]).

crustal deformation, subsidence, and intense sediment accumulation. This orogeny laid the foundation for complex stratigraphic layers, resulting in thick sequences of marine and terrestrial deposits interspersed with volcanic materials. These formations, now buried at significant depths, offer potential reservoirs for carbon storage, although their heterogeneity requires rigorous characterization [123, 124].

Variscan Orogeny

The late Paleozoic era was marked by the Variscan progeny (Fig. 7a), characterized by intense mountain building and tectonic activity. This era was affected by widespread folding, faulting, and the emplacement of extensive sedimentary sequences, especially pronounced in the southwestern regions of Poland. The Variscan orogenic belt facilitated the development of thick coal-bearing strata and significant clastic deposits, which not only have historical economic significance due to coal mining but also present potential for enhanced gas recovery and CO_2 sequestration. These structures, characterized by complex folding and thrusting, require advanced geophysical techniques for precise assessment [115, 115].

Alpine Orogeny

The Mesozoic to Cenozoic alpine orogeny further redefined the tectonic architecture of the region, especially influencing the Carpathian domain. This phase was associated with the evolution of foreland basins, such as the Carpathian Foredeep, which is notable for its significant structural complexity and is an ideal feature for geological storage. The intense tectonic reworking during the Alpine orogeny resulted in varied lithologies and created multiple stratigraphic traps, enhancing the potential for secure CO_2 storage. The resulting ultramafic sequences and flysch deposits, coupled with synorogenic turbidites, offer both opportunities and challenges in the realm of carbon capture and storage strategies [116].

Post-Orogenic Subsidence and Glacial Impact

Following these tectonic upheavals, Poland experienced extended periods of post-orogenic subsidence, which contributed to the development of extensive sedimentary basins, such as the Polish Basin. Moreover, glacial activity during the Quaternary period had a significant impact on erosion patterns and deposition processes, shaping Poland's current subsurface characteristics. Glacial deposits and moraines contribute to the modern landscape, influencing porosity and permeability patterns that are critical to evaluating the efficacy of storage sites. Understanding these glacial imprints, along with the transgressions and regressions that influence sediment distribution and compaction, is key to optimizing the storage potential [125, 126].

4.2 Tectonic setting

The sedimentary subsurface of Poland consists of a Precambrian crystalline basement overlain by an intricate assemblage of Phanerozoic sequences, which include clastics, carbonates, and evaporites. The present-day subsurface configuration of Poland is determined by three major tectonic domains: the East European Craton, the Teisseyre-Tornquist Zone, and the Carpathian orogen (Fig. 7). Influenced by the convergence of these tectonic domains, Poland's geological landscape presents both challenges and opportunities for CO_2 sequestration. The stratified nature and the varying subsurface characteristics across these regions mandate comprehensive geological assessments to unlock their full potential for carbon storage, thus playing a crucial role in broader carbon management strategies essential for mitigating the impacts of climate change [127].

The lithostratigraphic architecture of Poland is primarily defined by the following tectonic domains (Figs. 7- 8:

- **East European Craton (EEC):** This stable Precambrian basement underpins the northeastern part of Poland, including the Baltic Basin and the Polish Lowlands. The stability of the EEC has helped preserve extensive sedimentary sequences spanning from the Cambrian to the Quaternary periods. These sequences predominantly consist of sandstones, shales, and carbonates, which have undergone minimal tectonic deformation, making them favorable for hydrocarbon exploration and CO_2 storage [128].

- **Trans-European Suture Zone (TESZ):** Serving as a prominent NW-SE trending boundary, the TESZ delineates the transition between the ancient EEC and the younger Paleozoic platforms to the southwest. This zone is characterized by a complex assemblage of terranes and suture zones resulting from past collisional events. The TESZ has significantly influenced sediment dispersal patterns and basin evolution, acting as a conduit for sediment transport and affecting subsidence rates [128].

- **Carpathian Orogen:** Located in southern Poland, the Carpathian Orogen is a dynamic Cenozoic fold-thrust belt formed due to the Alpine orogenic processes. This region encompasses the Carpathian Foredeep, a flexural foreland basin characterized by intricate structural and stratigraphic patterns. The evolution of the orogen has been pivotal in shaping the sedimentary environments and the resource potential of the area [129].

These tectonic domains have nurtured the formation of several crucial sedimentary basins in Poland that are of interest for CO_2 storage (see also Fig. 8), including:

- Polish Lowlands Basin (PLB): A Permian-Mesozoic intracratonic basin.
- Carpathian Foredeep (CF): A Neogene foreland basin.
- Baltic Basin (BB): An offshore passive margin setting with Cambrian-Ordovician successions.
- Fore-Sudetic Monocline (FSM): A Permian rift-related depocenter.

4.3 Major Sedimentary Basins

The dynamic interplay between tectonic activity and sedimentary processes has intricately defined four major sedimentary basins in Poland, each distinguished by its complex geodynamic history and evolving geological characteristics. Figure 8 shows that these basins not only display unique sedimentary sequences but also present significant potential for both geoenergy exploitation and carbon sequestration initiatives. Their intricate geological features, formed through episodes of tectonic upheaval and sediment deposition, underscore the need for meticulous and tailored exploration programs. Such evaluations are crucial to unlocking each basin's full resource potential, advancing sustainable energy strategies, and contributing to Poland's efforts to mitigate the impacts of climate change through effective carbon management.

4.3.1 Polish Lowlands Basin (PLB)

The PLB is a significant Permian-Mesozoic intracratonic basin that extends across much of north-central Poland. Characterized by a voluminous succession of sedimentary rocks, including vast deposits of sandstones, shales, and carbonates, the PLB reflects a dynamic sedimentary environment facilitated by major tectonic events and subsequent subsidence [130, 131]. The evolution of this basin has undergone phases of extensional tectonics, followed by periods of thermal subsidence, resulting in the creation of substantial structural traps that are favorable for hydrocarbon entrapment. Among the notable hydrocarbon-rich provinces within the PLB, we identify:

- **Pomerania Province:** Situated in the northwest, Pomerania is notable for its potential hydrocarbon reserves, highlighted by extensive stratigraphic and basin analyses. Preliminary assessments indicate promising exploration targets, particularly within the Triassic and Jurassic sequences.

- **Wielkopolska Province:** Located in west-central Poland, this province showcases several hydrocarbon-bearing formations. Ongoing exploration actions focus on deep geological units, including Permian and Carboniferous strata, with the aim of discovering new viable oil and gas reserves within identified structural trends.

- **Małopolska Province:** Spanning southern Poland, Małopolska incorporates both conventional and unconventional hydrocarbon resources. Its stratigraphy reveals a promising potential given its diversified depositional settings, which encompass Paleozoic to Mesozoic sequences suitable for continuous exploration.

4.3.2 Carpathian Foredeep (CF)

The Carpathian Foredeep is a Neogene foreland basin located along the northern fringe of the Carpathian Mountains. It epitomizes a complex stratigraphic arrangement anchored by Miocene clastic deposits, predominantly sandstones and shales, which were laid down under foreland basin conditions amidst an active compressional regime [132]. The intricate geological setup fosters a variety of structural traps, including those associated with thrust faults and fold belts. The basin's hydrocarbon potentials are primarily concentrated in the following areas:

- **Lublin Province:** Situated in the east, Lublin has attracted significant exploration interest. Its Miocene strata, rich in potential reservoirs, have already revealed several hydrocarbon fields beneath structural traps, where lead activities target both conventional and unconventional reserves.

- **Gdańsk Province:** Located in northern Poland, Gdańsk is distinguished by the hydrocarbon potential within the Miocene and pre-Miocene formations. Ongoing evaluations seek to quantify recoverable resources through integrating geophysical surveys and drilling techniques.

4.3.3 Baltic Basin (BB)

The Baltic Basin is an offshore passive margin setting that extends beneath the Southern Baltic Sea, encompassing a remarkable Cambrian-Ordovician succession. Significant early Paleozoic sedimentation has produced a classical sequence of platform carbonates and siliciclastics, whose structural integrity affords promising sites for hydrocarbon exploration. Enhanced by regional geophysical data, the potential of the basin is encapsulated in its deep sedimentary sequences, which indicate dependable reservoirs [133, 133].

4.3.4 Fore-Sudetic Monocline (FSM)

The Fore-Sudetic Monocline (FSM) is a Permian rift-related depocenter in southwestern Poland. This structural feature was formed during the extensional tectonics associated with the Permian rifting phase, resulting in the deposition of thick sequences of volcaniclastic and sedimentary rocks. The FSM is characterized by its structural simplicity but has complex internal stratigraphy that offers considerable prospects for geological exploration, particularly within basal conglomerates and sealed structural highs [134].

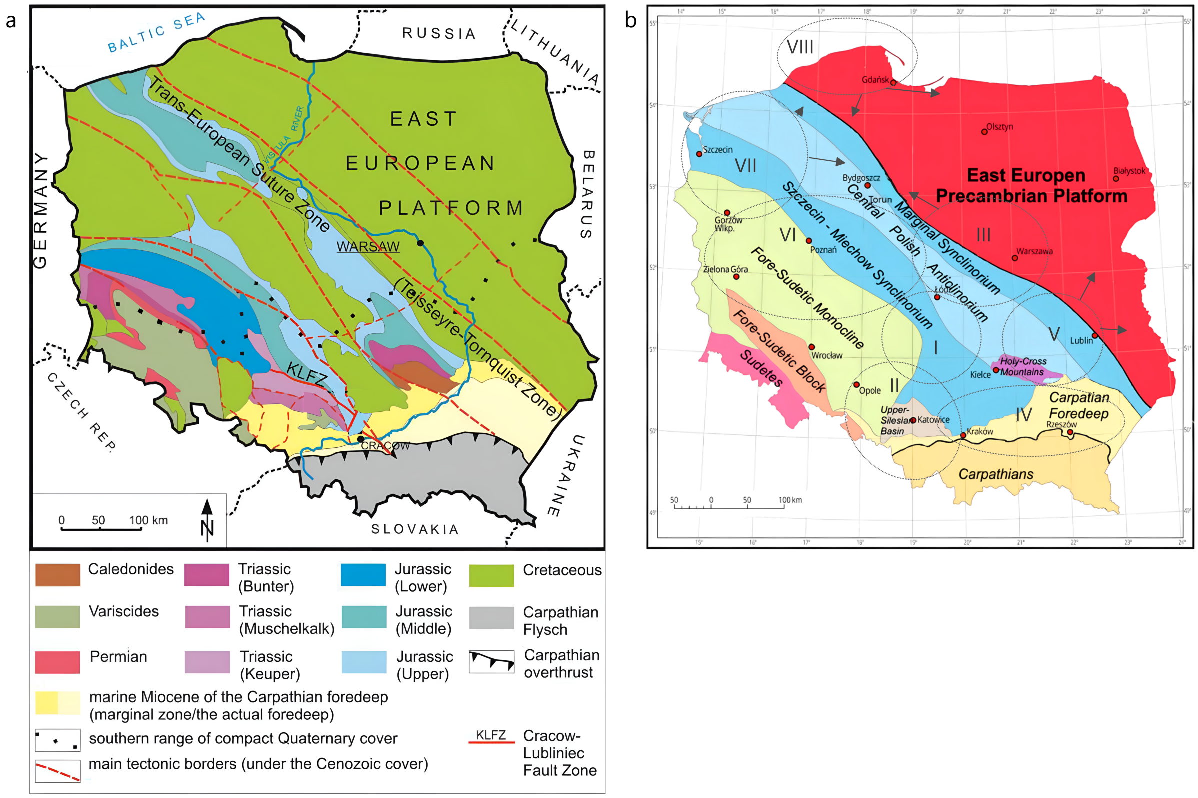

Figure 8: Geological framework and CO_2 storage potential in Poland subsurface sedimentary basins. (a) Simplified subsurface geological map of Poland, excluding Cenozoic cover, highlighting Mesozoic and Paleozoic formations relevant to storage potential assessments (modified from [135, 136]). (b) Distribution of geological basins and CO_2 storage evaluated regions, covering saline aquifers in eight regions (I–VIII, as in [86]) within Permian–Mesozoic formations (Bełchatów, Warsaw–Mazovia, Greater Poland–Kujawy, NW Poland), Paleozoic formations (Upper Silesian Coal Basin, Lublin–Podlasie, Łeba Elevation, Baltic Sea economic zone, NE Poland), and Mesozoic–Paleozoic formations in the Carpathian Overthrust and Foredeep. Additional storage options include depleted hydrocarbon fields (western and southeastern Poland). Unmineable coal beds (Upper Silesian Coal Basin) are also proposed provisionally in Poland but lack the necessary scrutiny.

5 Storage Potential of Sedimentary Basins in Poland

Poland's sedimentary basins, formed through complex multiphase tectonic evolution, offer diverse geological settings suitable for CO_2 storage. This section synthesizes stratigraphic, structural, and petrophysical data and interpretation sourced primarily from Poland's National CCS Assessment Project [86], evaluating storage potential across eight key study areas (I–VIII), as shown in Figure 8. A summary is provided in Table 2, recently updated through the EU CCUS ZEN project [106]. These assessments are primarily at the theoretical capacity level and correspond to SRL 1–3. These regions, however, may face potential land-use restrictions due to regulatory zoning, environmental considerations, Natura 2000 provisions, proximity to population centers, safety and security risks, and conflicts with other subsurface energy applications, further constraining these high-level theoretical CO_2 storage estimates presented below.

5.1 Onshore Basins

5.1.1 Polish Lowlands Basin (PLB) – Study Areas I, III, VI, VII

The Permian-Mesozoic PLB, covering 72% of Poland's territory, accounts for approximately 85% of the country's theoretical CO_2 storage potential. Key sub-regions include:

- **Bełchatów Zone (Study Area I):** Characterized by Lower Jurassic anticlinal traps such as Budziszewice-Zaosie and Wojszyce, these zones exhibit porosity ranging from 15–25% and are positioned in supercritical CO_2 conditions (35–70°C at depths of 775 to 2,265 m). Caprock integrity is ensured by a 100-m-thick Toarcian claystone with nano-darcy-scale permeability. **Key risk**: The proximity to Łódź potable aquifers necessitates targeted geochemical monitoring of brine-freshwater interfaces.

- **Mazovia Trough (Study Area III):** Featuring a multi-reservoir Jurassic-Cretaceous system (Bielsk-Bodzanów, Sierpc anticlines) with net sand thicknesses of 20-30 m, dynamic simulations indicate a capacity to handle industrial emissions from Warsaw-Płock, totaling 2.6 Gt. **Conflict**: This area overlaps with shale gas exploration licenses on the Lublin Basin periphery.

- **Fore-Sudetic Monocline (Study Area VI):** The Poznań Trough Megastructure houses Rotliegend volcaniclastics with a capacity of 634 Mt. Zechstein caprock integrity needs reinforcement, as 412 legacy wells exist that likely require re-cementation. **Innovation**: There is potential for CO_2-EGR in the adjacent depleted Wilków gas field with a 13.6 Mt capacity.

- **NW Poland (Study Area VII):** The Choszczno-Suliszewo Triassic-Jurassic structure boasts a significant theoretical capacity. A standout feature is its high permeability, enabling million-ton per annum injection rates; however, approximately 40% of this area intersects with NATURA 2000 zones, imposing limitations on surface infrastructure development.

5.1.2 Carpathian Foredeep (CF) – Study Area IV

The Carpathian Foredeep, a thrust-and-fold belt, offers dual storage mechanisms in:

- **Badenian Sandstones:** Deltaic turbidites with porosities of 18–22% are prominent at the Skoczów-Czechowice site (Study Area II). Seal integrity might be initially verified in the Menilite shales, although fault reactivation necessitates de-risiking and detailed site characterization.

- **Carboniferous-Devonian Carbonates:** The fractured Grobla and Niepołomice structures offer further major pore volume capacity, with enhanced permeability of the karst (50–200 mD) that facilitates the capture of dissolution

5.1.3 Lublin-Podlasie Region (Study Area V)

This region houses underexplored aquifers with a high-level theoretical static evaluation of several hundred megatons:

- **Carboniferous C3 Sands:** With a thickness of 30 meters and porosity ranging from 5–15%, the Stężyca IG-1 well shows promising reservoir properties. However, limited seismic coverage introduces uncertainty.

- **Cambrian Reservoirs:** The Podlasie regional aquifer, spanning 650 km^2 with a 200 m net sand thickness, could exhibit low storage efficiency in preliminary assessment due to structural complexity, necessitating detailed seismic surveys to characterize reservoir units, structures, and enable dynamic capacity assessments.

5.2 Offshore Basins – Study Area VIII

5.2.1 Baltic Basin

The Cambrian Deimena Formation sands within Poland's exclusive economic zone offer cross-border potential:

- Block B (Offshore): With salt-cored anticlines in the B3 field, this area could offer huge practical storage capacity. A high injectivity are expected within these units.
- Block E (Onshore): The Elbląg region's Cambrian sands, with significant storage capacity, align with the D6 structure in Kaliningrad, necessitating EU-mediated storage agreements and resolution of cooperation conflicts outlined in the introduction.
- The Middle Cambrian Debkowska Formation offers cross-border CO_2 storage potential, extending from Polish sandstone units into the Swedish aquifers of the Dalders Monocline (Faludden Formation). Using a conservative 2% storage efficiency for a semi-open aquifer, the recent CCUS ZEN evaluations estimate 747 Mt of storage capacity on the Swedish side and 188 Mt on the Polish side [137]. Additionally, two depleted hydrocarbon fields with structural traps in the same Polish unit provide further storage potential.

5.3 Coalbed Methane and CO_2 Storage – Study Areas II, III

The Upper Silesian Coal Basin may offer a potential for CO_2 storage through Enhanced Coal Bed Methane Recovery (ECBMR), though scientific and technical challenges, beyond the scope of this synthesis paper, require further exploration.

- **Pawłowice-Mizerów Site:** High-volatile bituminous coals with a methane content of 8–12 m^3/ton and a CO_2 adsorption capacity of 4.5 mmol/g. A pilot carried out between 2004 and 2008 confirmed a capacity of 5 to 8 Mt, although a 30% permeability loss due to matrix swelling was observed.
- **Dębowiec Beds (Miocene):** Identified as a secondary target in Skoczów-Czechowice with a capacity of 44 Mt, there is a risk of co-injection of methane from underlying Carboniferous layers, which makes monitoring of gas composition essential.

  The high water saturation (>80%) in Studzienice-Międzyrzecze can constrain injectivity. Cyclic CO_2-N_2 injection is proposed to alleviate capillary pressure and improve injectivity.

5.4 Implications for CO_2 Storage Deployment

Figure 9 and Table 2 provide a high-level overview of potential geological storage candidates with SRL 1–3 in Poland. Integrated synthesis assessments of Poland's sedimentary basins, including the Polish Lowlands Basin, Carpathian Foredeep, and Fore-Sudetic Monocline (Figure 8), indicate a significant but highly uncertain combined theoretical CO_2 storage capacity in saline aquifers of approximately 10 Gt (±25%, 7.5–12.5 Gt).

These aquifers exhibit favorable geological properties tailored for CO_2 sequestration. The Polish Lowlands Basin, with its Rotliegend and Buntsandstein sandstones, may theoretically contribute 6.7 $GtCO_2$, characterized by porosities of 12–18% and a broad permeability range at deep enough depths of $scCO_2$ sequestration. The Carpathian Foredeep offers 3.0–5.0 $GtCO_2$ within Badenian Sandstones and Sarmatian Carbonates. The smaller Fore-Sudetic Monocline adds 0.5–1.0 $GtCO_2$ from Rotliegend Volcanics and Zechstein Limestones, despite lower petrophysical properties.

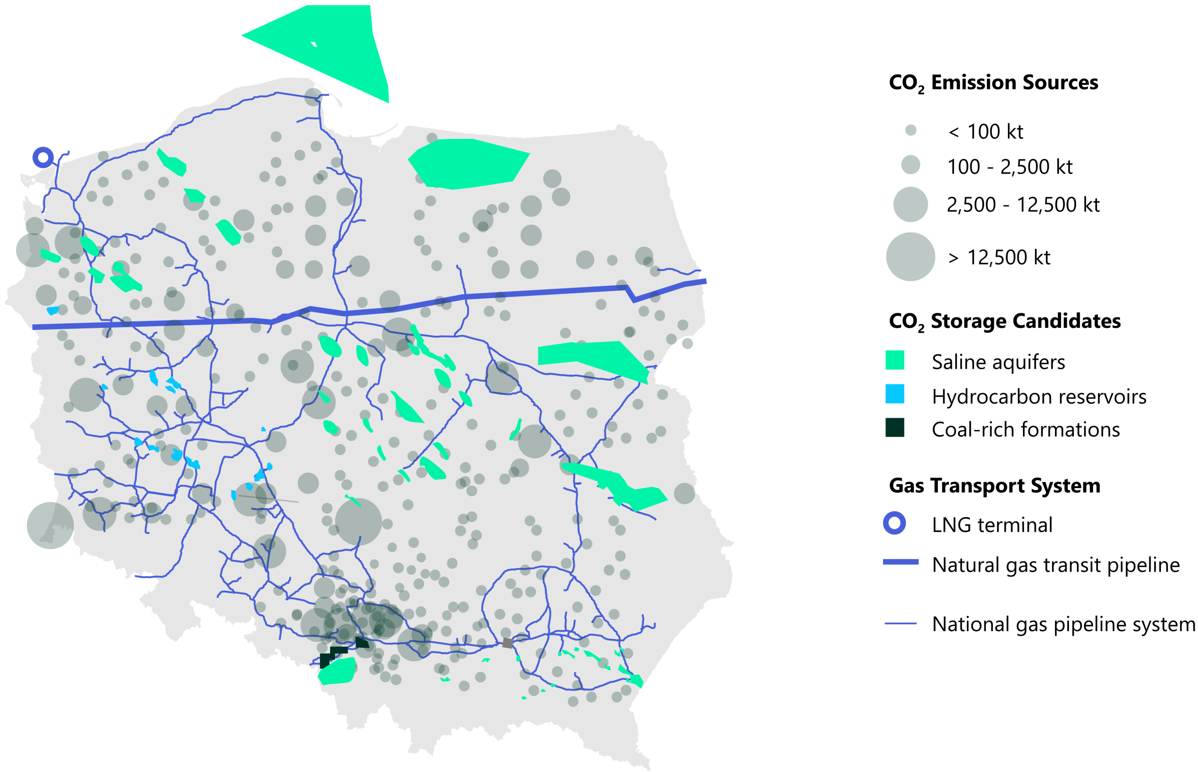

Figure 9: Map of major CO_2 emission point sources and high-level overview of potential geological storage candidates in Poland, illustrating the spatial distribution of industrial emitters and proximity to sequestration opportunities. Emission sources are categorized into four groups, with 102 facilities emitting >100 kt/year (totaling 189,183 kt/year in 2023), led by the power sector (83 facilities, 143,272 kt/year, 80% of industrial emissions), followed by cement (9 facilities, 11,723 kt/year), chemicals (15 facilities, 9,289 kt/year), and other industries like refineries and steel. Potential storage sites include deep saline aquifers, depleted oil and gas fields, and unminable coal beds. Land-use constraints from Poland's Natura 2000 network, covering 20% of the country's land area as part of the EU's ecological conservation framework, may restrict surface infrastructure for CO_2 sequestration in protected areas. Adapted from the Polish Geological Institute's Interactive Atlas Presenting Possibilities of CO_2 Geological Storage in Poland and [86, 16, 106, 33, 138].

Depleted hydrocarbon reservoirs in these onshore basins (Figure 9) supplement this capacity with practical CO_2 storage estimates of 0.1–0.5 Gt, leveraging existing infrastructure and geological data from prior hydrocarbon extraction. The Polish Lowlands Basin contributes the majority, with the Carpathian Foredeep providing additional capacity. Offshore, the saline aquifers of the Baltic Basin offer significant theoretical CO_2 storage capacity, as noted earlier. These reservoirs, composed of Cambrian-Ordovician sandstones, benefit from high porosities (20–28%) and high permeability values at comparatively shallow depths.

Recent evaluations by an EU project consortium [106, 137] identified 55 aquifer units and 5 hydrocarbon fields, with a storage readiness level of 2–3, yielding a total CO_2 storage capacity of 8.9 Mt at a 20% storage efficiency.

Coal seams in the Upper Silesian Coal Basin (Figure 9) might offer potential CO_2 storage via but not limited to, for instance, ECBMR. Although individual sites have limited capacity (early rough estimates of 0.01–0.1 Gt CO_2), developing multiple sites could cumulatively contribute to storage capacity, further incentivized by methane recovery economics.

The diverse lithostratigraphic framework and sedimentary architecture of the subsurface of Poland can provide a solid foundation for CO_2 storage:

- Onshore Storage: The proximity to industrial centers in the PLB and CF (Fig.9) minimizes transportation costs and facilitates integration with existing infrastructure. The significant capacities in the Rotliegend and Jurassic formations are especially attractive for large emitters.
- Offshore Storage: The extensive Cambrian-Ordovician sandstones of the Baltic Basin, coupled with high-quality Silurian shale seals, offer vast storage potential with reduced land-use conflicts. This option is particularly attractive as a complement to onshore storage.
- Coalbed Methane Recovery: Coal seams can theoretically provide both CO_2 storage and methane recovery, although their capacity and operation efficiency could be limited and site-specific.

Poland's high-level CO_2 storage capacity estimates range from approximately 8.9 Gt (SRL 2–3) to 10.2–12.7 Gt (SRL 1–2), provisionally up to 15 Gt, though technical and regulatory challenges, discussed in subsequent sections, persist. A hybrid approach integrating onshore and offshore storage, supported by rigorous monitoring, advanced reservoir simulation, and adaptive management, is essential to optimize CO_2 sequestration and achieve Poland's decarbonization goals.

6 Potential for Carbon Mineralization in Mafic and Ultramafic Rocks in Poland

Poland's geological setting, spanning the East European Craton, Bohemian Massif, and Carpathian orogenic belt, may provide a diverse substrate for carbon mineralization (via different strategies and approaches), particularly in mafic and ultramafic rock formations. These rocks, rich in magnesium-, calcium-, and iron-bearing silicates (e.g., olivine, pyroxene, serpentine), react with CO_2 to form stable carbonate minerals, such as magnesite and calcite, through mineral trapping. This process offers permanent sequestration, unlike saline aquifer or hydrocarbon field storage. Although Poland lacks extensive basalt plateaus like Iceland or ophiolite complexes like Oman, mafic and ultramafic rocks in the Sudetes Mountains, Upper Silesia, Holy Cross Mountains, Gorzów Wielkopolski region, and Tertiary volcanic provinces (e.g., Kaczawa Mountains, Złotoryja) present theoretical potential for carbon sequestration via CO_2 mineralization. This section synthesizes petrographic analyses and recent studies to evaluate their location, depth, distribution, properties, age, composition, alteration, and weathering, highlighting both opportunities and limitations.

6.1 Regional Distribution and Tectonic Context

The Sudetes Mountains in southwest Poland host the most significant mafic and ultramafic exposures, notably the Ślęża Ophiolite near Sobótka and the Nowa Ruda ophiolite, both part of the Variscan oceanic lithosphere (ca. 353 ± 21 Ma, Sm-Nd dating). The Ślęża Ophiolite, spanning approximately 20 km^2, features a pseudostratigraphy transitioning from serpentinites and gabbros in the south to metabasite lavas and pillow basalts in the north, with recent discoveries of epidosites (quartz + epidote + titanite) in its sheeted dyke complex indicating a supra-subduction zone affinity. Nowa Ruda, although smaller (<10 km^2) and tectonically fragmented, mirrors this composition with serpentinites and gabbros, which are also part of the Variscan suture.

In central Poland, the Holy Cross Mountains, part of the Trans-European Suture Zone, are characterized by Devonian to Carboniferous mafic volcanic rocks (approximately 400–300 Ma), including basalts and diabases, which are linked to Variscan rifting and extensional tectonics. Northwest Poland's Gorzów Wielkopolski Block, within the Fore-Sudetic Monocline, contains Permian Rotliegend metavolcanic rocks (andesite-basalts and andesites, 285 ± 5 Ma, K-Ar dating), overlying Paleozoic basement and underlying

Zechstein evaporites, providing a deep-seated target for mineralization. The Tertiary volcanic provinces in the Kaczawa Mountains and Złotoryja region feature Neogene basaltic lava flows, pyroclastic deposits, and volcanic necks like Ostrzyca, surrounded by Permian sandstones and conglomerates, with pervasive cooling fractures enhancing fluid migration. These formations are confined to tectonically active or ancient orogenic zones.

6.2 Depth, Distribution, and Petrophysical Properties

Depth and distribution vary depending on the tectonic context. The Ślęża Ophiolite ranges from surface exposures to depths of several kilometers, with some sections buried under Mesozoic-Cenozoic sediments at 1–5 km, as inferred from Soviet seismic profiles. Nowa Ruda follows a similar pattern, while Holy Cross Mountain exposures are shallow (<100 m), accessible for surface-based studies. Gorzów Wielkopolski's Permian metavolcanics, sampled from boreholes (e.g., Namyoelin 1, Witnica 1, Dzieduszyce 1), lie beneath thick sedimentary cover, reaching depths of 1–3 km, overlying Lower Carboniferous clastics and sealed by evaporites. Kaczawa and Złotoryja basalts, typically <200 m thick, are near-surface or shallowly buried, with Ostrzyca's fracture-rich structure enhancing accessibility. Laterally, these rocks are scattered: Ślęża at 20 km^2, Nowa Ruda and Upper Silesian basalts at <10 km^2 each, and Gorzów Wielkopolski's metavolcanics forming patchy lenses. Vertical heterogeneity, including faults and variable lithological continuity, necessitates high-resolution mapping to optimize CO_2 injection depths and mitigate risks like induced seismicity.

Petrophysical properties, age, and composition govern CO_2 reactivity. Generally, mafic rocks (basalts, gabbros) exhibit densities of 2.7–3.0 g/cm^3, porosities of 1–10% (up to 15% in fractured zones), and permeabilities of 10^{-19} to 10^{-15} m^2 (10–100 mD in fractures), driven by plagioclase, pyroxene, and minor olivine (45–52% SiO_2). Based on global studies, ultramafic rocks (peridotites, serpentinites) are denser (3.0–3.3 g/cm^3), with porosities of 5–15% and permeabilities of 10^{-16} to 10^{-13} m^2 (<1 mD intact), rich in olivine (MgO >18–50 wt%), pyroxene, and serpentine (SiO_2 <45%), plus accessory chromite and magnetite. Ślęża's chromitites show variable Cr# (0.41–0.68) and Mg# (0.62–0.83), with ferrogabbros containing up to 14.6 vol% magnetite-ilmenite. Gorzów Wielkopolski's andesite-basalts preserve subalkaline basalt signatures despite low-grade metamorphism (<200°C, 2 kbar), with assemblages like pumpellyite and laumontite. Kaczawa basalts, fine-grained and fractured, may have enhanced carbonation kinetics.

6.3 Age, Composition, and Alteration

Ages span Neoproterozoic to Early Paleozoic for Sudetes, Devonian-Carboniferous for Upper Silesia and Holy Cross, Permian for Gorzów Wielkopolski, and Neogene for Kaczawa/Złotoryja, reflecting Poland's complex tectonic evolution. Compositions include mafic rocks dominated by plagioclase, pyroxene, and minor olivine (SiO_2 45–52 wt%), and ultramafic rocks rich in olivine (MgO 18–50 wt%), pyroxene, and serpentine (SiO_2 <45 wt%), with accessories like chromite and magnetite. Alteration and weathering significantly influence suitability. Serpentinization dominates Sudetic ultramafic rocks, converting olivine to serpentine, magnetite, and brucite, increasing porosity but depleting reactive silicates, with natural magnesite and calcite veins forming under Poland's temperate climate. Gorzów Wielkopolski's metavolcanics show pervasive low-grade metamorphism, replacing primary minerals with corrensite and zeolites, leaving rare clinopyroxene and Cr-spinel. Mafic rocks show milder alteration (chloritization, epidotization), with weathering occurring shallowly (<100 m) and being fracture-enhanced in the Kaczawa basalts, although it is slow compared to tropical rates.

6.4 Suitability for CO_2 Mineralization

CO_2 mineralization suitability hinges on reactivity, volume, and accessibility. As established in experimental studies, ultramafic rocks offer high uptake (0.62 t CO_2/t olivine, 0.4–0.5 t CO_2/t serpentine), with fresh peridotites rapidly forming magnesite, while mafic rocks provide 0.3–0.4 t CO_2/t basalt via Ca/Mg-rich minerals. Preliminary capacity estimates, based on conservative rock volumes and efficiency factors ranging from 1% to 20%, suggest Ślęża's 20 km^2 might theoretically and provisionally store 1–10 Mt CO_2, Nowa Ruda and Holy Cross sites 5–20 Mt each, Gorzów Wielkopolski and Kaczawa/Złotoryja similarly limited. Low ultramafic permeability necessitates hydraulic fracturing, while fractured mafic rocks (e.g., Ostrzyca) enhance injectivity, though deep reservoirs (>1 km) elevate drilling costs. In-situ mineralization suits both rock types, with supercritical CO_2 viable for basalts as well.

Poland's mafic and ultramafic rocks may theoretically provide localized CO_2 storage solutions for distributed emitters, particularly in pilot-scale projects. However, their limited volumes, extensive alteration, low permeability, and insufficient site-specific data hinder scalability relative to Poland's annual CO_2 emissions. Detailed site characterization and reactive transport modeling are essential to establish scientific foundations and address technical challenges.

7 Discussion

Poland is intensifying its efforts to combat climate change by developing and deploying CCUS technologies in response to the pressing need to curb greenhouse gas emissions. These initiatives are embedded within an evolving national framework aimed at achieving substantial emission reductions. Recognizing the specific challenges associated with its coal-dependent energy sector, Poland emphasizes the importance of adopting solutions to facilitate a transition to a sustainable energy system. Central to this strategy is geological storage, also known as carbon sequestration, which serves as the final critical stage of the CCUS value chain in Poland. Beyond emission reduction, Poland seeks to integrate carbon capture with utilization pathways, such as synthetic fuel production or enhanced resource recovery, to unlock economic benefits while aligning with the European Union's ambitious climate targets. This dual focus on mitigation and economic opportunity underscores a commitment to climate action, striking a balance between environmental imperatives, energy security, and industrial competitiveness.

7.1 Geological Storage: The Cornerstone of CCS

Geological carbon storage serves as both a technical necessity and a strategic asset to advance Poland's decarbonization goals. Poland's geological landscape provides diverse formations suitable for large-scale CO_2 sequestration, primarily in deep saline aquifers and depleted hydrocarbon reservoirs. Unmineable coal beds and carbon mineralization in mafic and ultramafic rocks may also contribute, pending rigorous evaluation. The country's primary CO_2 storage capacity is concentrated in three major geological regions (Figs. 8-9: the Polish Lowlands, the Baltic Basin, and the Carpathian Foredeep [139, 86, 106]. These regions are characterized by sedimentary formations with favorable reservoir characteristics, and the presence of thick caprock layers composed of mudstone/shale or anhydrite [140]. Beyond mere categorization as outlined below, the choice of storage sites necessitates detailed geological characterization:

- Deep Saline Aquifers: These formations are considered the most promising and contribute to approximately 90–93% of Poland's total geological storage potential. Their abundance and capacity for large storage volumes make them ideal for sequestration. Widespread availability and proximity to emitter sites (Fig. 9) can position them as a key domestic solution for CO_2 storage.

- Depleted Oil and Gas Reservoirs: These reservoirs, having served previously in hydrocarbon extraction, present a viable storage option, contributing about 7 to 10% to the total potential. Their existing infrastructure, data availability for site-specific characterizations, and proven containment capabilities offer advantages in terms of cost-effectiveness, deployment period, and safety despite smaller storage capacity compared to saline aquifers.

Although technically feasible, CO_2 storage in coal seams accounts for less than 1% of the potential capacity, rendering them a minor component in the overall sequestration strategy due to their limited volume [86]. Carbon mineralization in Poland's mafic and ultramafic rocks could also offer a promising avenue for permanent CO_2 sequestration. However, its potential remains theoretical due to limited research and inadequate site-specific characterization. For unmineable coal beds and carbon mineralization in mafic and ultramafic rocks, detailed petrographic analyses, flow and reactive transport studies, THMC modeling, and field-scale pilot tests are essential to quantify CO_2 storage capacity and efficiency and address current limitations.

Onshore saline aquifers, such as the Konary structure near Poznań, with a notable initial storage capacity, are within 100 km of several major emitters in the region. Yet, local governments in Wielkopolska vetoed a 2023 injection permit, citing seismic risk fears despite PGI's probabilistic hazard assessment ($<$0.1% annual probability of M$>$2.0 quakes) [141]. Independently, the newly finalised EU networking project CCUS ZEN selected this site as one of the most promising CCUS storage sites [137, 142]. The assessment results suggested storing in the Konary and Kamionki aquifer structures located nearby four emitter subclusters (total of CO_2 emission is 8.187 Mt/year), where CO_2 can be delivered with pipelines of length 4-38 km [142].

The Baltic Basin, a legacy hydrocarbon province, is notable for its Cambrian and Devonian sandstone reservoirs. These structures, historically explored for oil and gas, can now be repurposed as priority CO_2 storage candidates, with estimated capacities of 3.8 Gt in saline aquifers alone [143, 86]. The Baltic Basin offshore sites' proximity to Gdańsk's ECO_2CEE terminal (50 km) minimizes transport costs but requires subsea pipelines through ecologically sensitive Baltic habitats, triggering opposition from stakeholders.

A unique strategic advantage lies in Poland's repurposing of depleted oil and gas fields or implementing enhanced oil/gas recovery, such as the Barnówko-Mostno-Buszewo (BMB) field in western Poland. With 85% of hydrocarbons extracted, BMB's Lower Jurassic reservoirs, equipped with existing wells and subsurface data, could store 220 Mt CO_2, leveraging legacy infrastructure to reduce capital expenditures by 40%. Similarly, the Zaosie anticline, a former gas storage site, might offer a "plug-and-play" solution with proven injectivity and real-time monitoring systems.

Comprehensive, site-specific characterization is essential for evaluating and optimizing CO_2 storage candidates in Poland, given the diverse geological settings of potential reservoirs, which exhibit significant variations in structural, lithological, and hydrogeological properties. This detailed assessment, encompassing stratigraphic architecture, reservoir quality and their distributions, caprock integrity, and fault stability, is crucial to ensure the safe, efficient, and long-term containment of CO_2, thereby mitigating risks such as leakage or pressure-induced seismicity that could compromise storage operations. As an example, early assessments presumed thick mudstone or claystone caprocks guaranteed effective sealing and structural integrity for CO_2 storage. However, recent studies demonstrate that, even in clay-rich caprocks at significant depths, petrophysical, physical, and geomechanical properties can vary by orders of magnitude [144, 145, 146, 147, 148], profoundly affecting leakage risk assessments and maximum allowable pressure buildup. These variations necessitate advanced characterization to ensure long-term containment security.

Each candidate site presents distinct advantages, such as the high storage capacity or the established infrastructure of onshore depleted gas fields, alongside constraints like complex fault networks or variable aquifer salinity. Central to this characterization is the integration of Thermo-Hydro-Mechanical-Chemical (THMC) processes, which collectively dictate reservoir performance and containment security. For instance, in several saline aquifers with elevated salinity levels (>10,000 mg/L), both onshore (e.g., Polish Lowland Basin) and offshore (e.g., Baltic Sea), CO_2 injection can trigger salt precipitation as a significant THMC challenge, where dissolved salts crystallize due to CO_2-induced evaporation-precipitation [149, 150, 151, 152], potentially clogging pore spaces, reducing injectivity, and compromising the containment integrity of these reservoirs [153, 154, 155, 156].

Selecting between onshore and offshore CO_2 storage scenarios is not straightforward, as neither is inherently superior. Hybrid approaches and inclusive strategies are recommended to optimize storage potential and address diverse geological, regulatory, and socio-economic considerations. Onshore reservoirs, such as the Kamionki anticline in central Poland, offer proximity to industrial emission clusters in Łódź and Warsaw, minimizing transport costs and infrastructure complexity [157]. Saline aquifers Karmionki J and K are also suggested to be suitable storage sites with their close location to emitters from refineries and power plants (6,9 Mt/year), with short infrastructure such as pipelines needed (e.g. [137]. However, public opposition rooted in perceived risk, such as groundwater contamination, induced seismicity, and land-use conflicts, has slowed permitting. A 2023 survey revealed that 62% of residents near proposed onshore sites oppose storage, citing insufficient transparency (refer to subsequent sections). The advantages of onshore storage include the relative proximity of emission sources to potential storage sites, which may reduce transportation costs and logistical complexities. Moreover, onshore storage can be closely monitored and managed by national authorities, ensuring compliance with environmental and safety regulations.

In contrast, offshore reservoirs in the Baltic Sea and Pomeranian Basin circumvent land-use disputes. The Baltic Cambrian Formation, located 80–150 km offshore, provides a significant capacity with Zechstein evaporites as caprock units. Yet, offshore development faces regulatory ambiguity under the Helsinki Convention, which restricts sub-seabed storage without the unanimous approval of Baltic Sea states. Additionally, offshore infrastructure costs are 30–50% higher than onshore alternatives, driven by subsea wellhead systems and corrosion-resistant materials [158, 159].

Offshore storage in open-access licenses, such as those in the North Sea, offers a viable option for CO_2 sequestration [16]. Projects such as Northern Lights in Norway [160] exemplify the potential of using offshore geological formations for CO_2 storage. The North Sea offers extensive sedimentary basins with proven capacity for CO_2 storage [16, 161], supported by decades of experience in the oil and gas industry. However, the offshore route is not without challenges. Transporting CO_2 from Poland to storage sites in the North Sea necessitates the development of robust infrastructure, including pipelines and purification facilities, to ensure that the captured CO_2 meets the stringent quality standards [162, 163]. These additional processing steps can increase costs, potentially making offshore storage less economically attractive compared to onshore alternatives [158, 164]. Furthermore, the offshore option may involve navigating regulatory frameworks that span multiple jurisdictions, adding a layer of administrative and technical complexity.

Despite these challenges, both onshore and offshore storage options present viable pathways to advance CCS initiatives in Poland. Selecting the most suitable storage strategy requires a multifaceted assessment of multiple factors. As Figure 5 demonstrated, it means maturing towards higher storage readiness levels. Given the challenges and opportunities of both onshore and offshore CO_2 storage, a single approach is unlikely to be sufficient. A diversified approach that leverages a wide range of geological storage options will be crucial to Poland's decarbonization objectives. This strategy should be supported by robust scientific research, cutting-edge engineering solutions, and a proactive policy framework that encourages investment in CCS infrastructure. In addition, it should align with the broader European commitment to climate neutrality, ensuring that Poland's initiatives are consistent with the

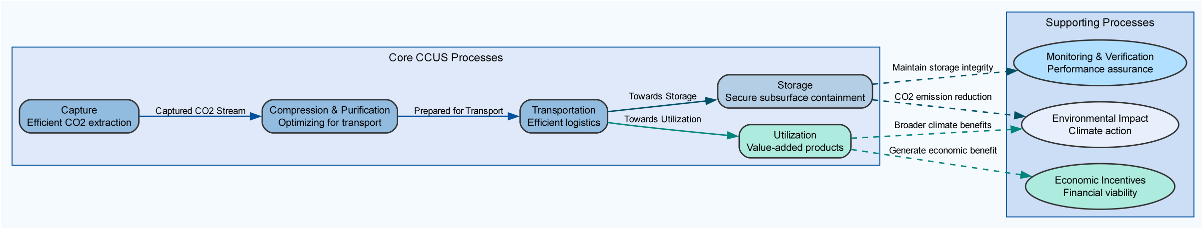

Figure 10: Schematic representation of the Carbon Capture, Utilization, and Storage (CCUS) value chain. This diagram illustrates the flow of CO_2 from capture to utilization and storage, along with its supporting processes. Captured carbon dioxide is compressed and purified to facilitate efficient transport to either geological storage sites or utilization in industrial processes. Supporting mechanisms, such as thorough monitoring, ensure containment integrity, while economic incentives foster adoption. Solid arrows depict core material flows; dashed arrows indicate enabling processes augmenting the value chain.

EU's objectives and best practices.

7.2 Integration within the Value Chain

As Figure 10 outlines the deployment of large-scale CO_2 storage sites in Poland hinges on robust integration across the CCS value chain, which encompasses five interdependent stages: (i) capture, (ii) compression and purification, (iii) transport, (iv) utilization and (v) storage, each requiring specialized technical, economic, and regulatory solutions. This holistic approach transforms CO_2 from an industrial byproduct into a managed resource, aligning infrastructure, policy, and market mechanisms to build a resilient and scalable system (Fig. 10). Effective integration is critical to Poland's decarbonization strategy under its Energy Policy 2040.

Strategic site selection underpins this integration, balancing geological suitability, proximity to emission sources, and public acceptance [165, 166, 167]. Poland's CO_2 storage capacity is distributed in various geological formations, necessitating a regionally tailored approach to connect emitters with reservoirs. The hybrid "cluster-and-hub" model optimizes this linkage: dense industrial zones like Upper Silesia, responsible for 40% of Poland's emissions [33], connect directly to local storage via short pipelines, while smaller, dispersed emitters feed into regional hubs for aggregation and large-scale sequestration or utilization. For example, a hub in Gdańsk could function as a major domestic and international CO_2 transit point, facilitating both domestic industrial applications and offshore storage options, particularly in the Baltic and North Seas.

Efficient CO_2 transport infrastructure is essential to bridge capture sites and storage reservoirs, enhancing CCUS scalability [168, 169, 170, 171, 163]. Poland is actively evaluating multiple transportation modalities, each with distinct advantages and constraints in terms of cost, scalability, and geographic feasibility. The most ambitious initiative in this regard is the proposed 1,200 km backbone pipeline, estimated to cost €2.1 billion, which aims to connect Upper Silesia with Baltic offshore storage sites. With a projected transport capacity of up to 20 million tonnes per annum (Mtpa) by 2040, this pipeline is expected to become the core transport artery for Poland's CCUS network. However, major technical and regulatory challenges remain, particularly in terms of construction costs in mountainous regions, land acquisition negotiations, and integrating with existing energy infrastructure corridors. These obstacles necessitate a phased implementation strategy, with initial construction prioritizing high-emission industrial clusters, followed by gradual expansion to include additional regions.

For smaller-scale emitters, direct pipeline access may not be cost-effective, so alternative transport solutions, such as rail and barge transport, may be required. Liquefied CO_2 rail transport remains an attractive option, albeit with higher operational costs of €15–20 per tonne, compared to €8–12 per tonne for pipeline transmission. The feasibility of this approach is further limited by rail network capacity constraints and terminal infrastructure availability, making it a secondary transportation method rather than a primary solution. Additionally, Poland is exploring a barge-based CCUS corridor on the Oder River, inspired by the thriving Rhine CCUS corridor in Western Europe. This initiative could help transport CO_2 from cement plants in the Wrocław region to storage hubs, but seasonal water level fluctuations present a significant reliability challenge.

Beyond domestic transport, maritime shipping is emerging as a strategic solution for international CO_2 movement. A prime example is the ECO$_2$CEE Project of Common Interest, which proposes a CO_2 export terminal in Gdańsk to collect emissions from Poland, Czechia, and Slovakia for shipment to Norway's Northern Lights storage facility. Although maritime transport provides flexibility, allowing Poland to mitigate domestic storage delays, it comes with significant technical and financial constraints. CO_2 must be purified to a purity level of 99. 9% before shipment to comply with stringent maritime safety regulations, adding an estimated € 25-30 per tonne to the total cost. Furthermore, reliance on foreign offshore storage sites raises concerns about long-term energy sovereignty and economic independence, especially given the potential geopolitical fluctuations in international carbon storage agreements.

Integration also demands rigorous monitoring and risk management to ensure storage security and environmental integrity [172, 173, 174, 43]. Advanced reservoir simulation models, real-time geophysical monitoring, and geochemical assessments play a crucial role in tracking CO_2 plume movement, pressure buildup, and potential leakage risks. These systems, critical for regulatory compliance and public trust, counter historical opposition to CCS in Europe (e.g., Barendrecht, Netherlands, 2010), particularly given Poland's seismic and groundwater concerns [43].

Beyond geological storage, CO_2 utilization (CCU) offers a complementary pathway that can turn emissions into value-added products, enhancing the economic viability of CCUS (Fig. 10). In Poland, emerging research and pilot initiatives are exploring the conversion of captured CO_2 into synthetic fuels, polymers, and mineralized building materials. For instance, CO_2-curing concrete technologies—currently under evaluation by Polish construction consortia—could absorb significant volumes of industrial CO_2, aligning with circular economy goals. Additionally, utilization in the chemical sector, such as urea production or methanol synthesis, presents near-term opportunities, particularly if integrated within industrial clusters where hydrogen and CO_2 streams can be co-located. However, CCU deployment faces economic and policy hurdles, including high energy requirements, low product margins, and limited regulatory recognition in carbon accounting frameworks. As such, while utilization will not replace storage as the dominant mitigation pathway, it holds potential to reduce net costs and promote early-stage CCUS adoption, particularly in hard-to-abate sectors.

7.3 Infrastructure, Regulatory, and Financial Considerations

Establishing a robust CO_2 storage network in Poland extends beyond technical feasibility, requiring a cohesive strategy that integrates infrastructure, regulatory clarity, and financial support to drive decarbonization [175]. These pillars ensure a smooth transition from fossil fuel dependence to a low-carbon economy. Without a well-defined regulatory framework and adequate financial backing, even the most technically feasible storage projects risk delays or failure due to uncertainty in permitting processes, lack of investor confidence, and insufficient infrastructure readiness.

Infrastructure Development: Poland's commitment to CCUS necessitates the establishment of a robust infrastructure for CO_2 transport and storage. This involves constructing new pipelines, compression stations, and monitoring systems, as well as evaluating the repurposing of existing natural gas pipelines. Retrofitting these pipelines for CO_2 transport is economically advantageous, potentially requiring only 1–10% of the capital expenditure needed for new infrastructure [176]. However, this approach depends on technical considerations such as pipeline integrity, material compatibility with CO_2 in various phases, and adherence to safety standards concerning corrosion resistance, pressure stability, and temperature management [168].

The distinct thermophysical properties of CO_2, differing from natural gas, necessitate modifications in pipeline materials, flow dynamics control, and compression requirements. In supercritical or dense-phase conditions, CO_2 exhibits higher density and lower viscosity, impacting transport efficiency and operational stability. Additionally, water impurities in CO_2 streams can form carbonic acid, accelerating corrosion. Mitigation strategies include applying corrosion-resistant coatings, installing internal linings, and implementing pressure-regulated control systems. Assessments of operating pressures, temperature fluctuations, and potential stress points are essential to prevent material fatigue and leakage over time [177].

Implementing real-time monitoring systems is crucial for ensuring long-term reservoir integrity and mitigating operational risks. Advanced seismic sensors, pressure gauges, and continuous well-logging technologies facilitate early detection of potential leaks, pressure anomalies, and unexpected geomechanical changes. Integrating these systems with digital twin modeling enhances performance forecasting, risk analysis, and regulatory compliance [168].

Recognizing the absence of dedicated CO_2 pipelines, Poland is developing a dedicated CO_2 transport network utilizing both new and existing infrastructure. A flagship initiative is the ECO2CEE project, an open-access, multi-modal CO_2 terminal at the Port of Gdańsk, connecting Polish industrial emitters with offshore storage sites via the European CO_2 transport network in the North Sea basin. Scheduled to commence operations by mid-2026, the terminal aims to handle approximately 3 million tonnes of CO_2 annually, with plans to expand capacity in subsequent phases [55]. Its designation as an EU Project of Common Interest ensures streamlined permitting and eligibility for EU funding through the Connecting Europe Facility.

In parallel, Poland's state-owned gas transmission operator, GAZ-SYSTEM, is collaborating with neighboring transmission system operators in Central Europe to explore regional CO_2 transportation solutions. These partnerships aim to integrate Poland's CO_2 network with broader European initiatives, potentially repurposing or co-locating with existing natural gas pipeline corridors for efficiency and cost savings. GAZ-SYSTEM's ongoing projects, such as the construction of the Gustorzyn-Wronów gas pipeline, exemplify efforts to enhance the country's gas transmission infrastructure, which could be pivotal for future CO_2 transport endeavors.

Strategically, Poland is leveraging existing assets and multi-modal transport options to expedite CCUS deployment. Given the capital-intensive nature of building an extensive pipeline network from scratch, policymakers are considering consortia of emitters or direct state investment to develop shared CO_2 pipelines. This approach envisions a state-owned entity managing a national CO_2 transportation network, ensuring open access and standardized operations. In the interim, a multi-modal CO_2 transport network utilizing pipelines, rail, road, and ship transport is planned to link emission sources and storage sites flexibly. Existing port infrastructure on the Baltic coast, such as in Gdańsk, is being adapted for CO_2 handling, demonstrating the repurposing of industrial assets for CCUS. Additionally, proposals to create a category of "direct CO_2 pipelines" in law aim to simplify connecting capture installations directly to storage sites, accelerating point-to-point infrastructure development. [178] proposes a new Project of Common interest (PCI) as an extension to the planned ECO2CEE PCI, with the export terminal in the Port of Gdansk. They suggest a new transport pipeline from northern Poland and Southeastern Lithuania to the Port of Gdańsk. Potentially, emissions from Czechia transported by railway can also be considered. Phase 2 of PCI should have a transport capacity at 9 $MtCO_{2/\mathrm{year}}$.

Safety measures are integral to Poland's infrastructure development, given the importance of public acceptance and operational security in CCUS. Past setbacks have shown that public concerns over

CO_2 leakage can impede projects, even when scientific evidence indicates such fears are unwarranted. In response, Polish authorities and stakeholders are prioritizing stringent safety standards and transparency in the design of transport and storage systems. The government's CCS legislation mandates extensive monitoring for large-scale CO_2 storage projects, with findings informing long-term strategies and reassuring the public of the technology's safety. Aligning with international best practices, Poland is adopting uniform technical standards, such as ISO guidelines for CO_2 capture, transport, and storage, to govern project development. Technical regulations are being drafted to specify pipeline material requirements, safe operating conditions, and connection protocols for linking capture installations to the CO_2 network. To build confidence, policymakers are advocating for small pilot storage projects to demonstrate secure underground injection in Poland's geology, providing empirical evidence of storage integrity to skeptical communities. A fit-for-purpose risk assessment framework is also under development to evaluate and mitigate hazards associated with CO_2 transport and sequestration. By proactively addressing safety through regulations, standards, and field demonstrations, Poland aims to ensure that its emerging CO_2 transport network and storage sites operate with minimal risk, thereby gaining public trust as the infrastructure scales up.

Regulatory Frameworks: The successful implementation of CO_2 storage depends on the establishment of clear and supportive legal frameworks that provide regulatory certainty and ensure compliance with environmental and safety standards. In Poland, the evolving regulatory landscape is increasingly focused on developing rigorous guidelines for site selection, injection protocols, risk management, and long-term monitoring [179]. The introduction of recent amendments to the Geological and Mining Law has significantly improved the legal foundation for onshore CO_2 storage, addressing previous regulatory gaps that hindered large-scale deployment [180].

A key aspect of these legal reforms is the precise definition of liability responsibilities, ensuring that operators remain responsible for the integrity of the storage site throughout the operational phase and beyond. These amendments also establish clear long-term monitoring obligations, requiring a continuous assessment of CO_2 plume behavior, pressure fluctuations, and potential leakage risks. By enforcing strict environmental and safety compliance criteria, the updated regulations aim to mitigate risks associated with underground storage while fostering investor confidence.

Regulatory clarity plays an essential role in attracting financial investment and encouraging industrial stakeholders to participate in CCUS projects. Unclear liability frameworks and ambiguous site closure requirements have historically discouraged private-sector participation in CO_2 storage ventures [181]. However, streamlined permitting processes and well-defined remediation protocols can reduce financial uncertainties for investors while ensuring that operators adhere to stringent safety standards throughout the CO_2 injection and post-closure phases.

Beyond investor confidence, public acceptance of CCUS technology remains a critical challenge in Poland. Societal concerns regarding storage safety, groundwater contamination, and induced seismicity have contributed to opposition against onshore CO_2 storage projects [182]. Addressing these concerns requires transparent regulatory mechanisms, enhanced public engagement strategies, and accessible risk communication. Evidence from other European countries indicates that public trust in CCUS projects is significantly higher when regulatory frameworks include strict independent monitoring and well-defined emergency response plans [183].

Poland's regulatory framework for Carbon Capture, Utilization, and Storage (CCUS) has recently undergone significant reforms to align more closely with European Union directives, facilitating the deployment of CCUS technologies. In October 2023, amendments to the Geological and Mining Law came into effect, lifting previous restrictions that limited CO_2 storage to demonstration purposes and offshore sites. These changes now permit onshore CO_2 storage and introduce incentives for smaller-scale projects, thereby removing several regulatory barriers that previously hindered the development of CCUS initiatives.

The recent amendments have also simplified the regulatory process for CCUS projects. Notably, the requirement to obtain an exploration and recognition license has been replaced with a decision approving a geological work project, streamlining the initiation of CCUS activities. Additionally, the amendments allow for the combination of CO_2 injection with enhanced hydrocarbon recovery methods, potentially improving the economic viability of CCUS projects.

These legislative changes reflect Poland's commitment to establishing a supportive legal framework for CCUS, aiming to accelerate the transition from demonstration projects to full-scale commercial deployment. By aligning domestic regulations more closely with EU guidelines and removing previous restrictions, such as the prohibition of onshore storage, Poland is creating an environment conducive to the advancement of CCUS technologies.

Financial Mechanisms and Investment: Large-scale financial investment is crucial for deploying CO_2 storage projects. Poland has allocated significant funding, including from the Energy Transformation Fund, to support CCUS infrastructure, research, and risk management advancements [184]. These investments aim to bridge the gap between technological readiness and large-scale commercial deployment while enhancing industrial competitiveness under the EU Emissions Trading System (EU ETS) [185].

The economic benefits of CCUS extend beyond emissions reduction. Industries integrating carbon capture can lower compliance costs and explore CO_2-enhanced oil recovery (CO_2-EOR), which extends oil field life and generates revenue [186]. Public-private partnerships (PPPs) and EU structural funds play a crucial role in derisking investments and accelerating scalability [184]. Tax incentives, similar to Section 45Q in the US, could stimulate private sector involvement in Poland.

International cooperation is another key driver. Poland's participation in regional initiatives, such as the Baltic Sea CCUS network, allows collaborative financing and integration with European carbon storage centers [175]. The proposed CO_2 export terminal in Gdańsk exemplifies how cross-border partnerships enhance economic feasibility.

Scaling up CCUS in Poland will require substantial investment and innovative funding mechanisms, drawing on both domestic and international support. Due to the high capital costs of carbon capture facilities and CO_2 transport infrastructure, Poland is actively exploring a variety of financial sources. European funding mechanisms, such as the EU Innovation Fund, are crucial to supporting initial demonstration and pilot projects by making economically marginal initiatives more viable. The planned Gdańsk CO_2 terminal, recognized as a Project of Common Interest by the European Union, exemplifies how European funding can facilitate critical infrastructure projects.

Past experiences have highlighted the importance of blended financing and government support. For example, the earlier attempt at the Bełchatów CCS project demonstrated that even significant EU funding could be insufficient without complementary domestic financial guarantees. Reflecting on such lessons, Polish authorities are currently developing strategies to reduce investment risks, including offering state-backed guarantees or insurance for CO_2 storage liabilities and establishing incentive structures that reward emission reductions.

Public–private partnerships (PPPs) are central to Poland's CCUS investment strategy. Recognizing the substantial investment required, the Polish government is encouraging collaboration between industry players and public entities, where public funding or EU financing may cover a portion of initial capital costs for carbon capture installations, particularly in industries urgently needing decarbonization. Concurrently, private companies could manage ongoing operational expenditures. For transport and storage infrastructure, considered natural monopolies, substantial state involvement and EU financing are anticipated.

To stimulate private sector investment, Poland is examining innovative financial instruments such as Carbon Contracts for Difference (CCfDs), which offer operators a guaranteed minimum price for CO_2 emissions reductions. Under such agreements, the government would compensate the operator if the carbon market price falls below an agreed threshold, making carbon capture economically viable and incentivizing early project development.

Furthermore, Poland is benefiting from international collaborations and financing partnerships. Notable initiatives include cooperation with Norway's Northern Lights CO_2 storage project under the EU-funded ACCSESS program, which explores transporting captured industrial CO_2 from Polish facilities, like the cement plant at Górażdże, to storage locations in the North Sea. Additionally, Poland is participating in regional discussions on developing a Central European CO_2 transport pipeline network, potentially connecting capture sites within Poland to international storage facilities. These collaborative, cross-border projects demonstrate how multinational partnerships can attract broader investment, pool financial resources, and integrate national infrastructure with regional and European networks.

7.4 Measurement, Monitoring and Verification (MMV)

The successful implementation of geological CO_2 storage in Poland depends on the deployment of MMV measures to address technical, regulatory, and societal challenges. Though a newer player, Poland requires comprehensive MMV frameworks to mitigate risks, ensure regulatory compliance with EU directives, and improve public trust through transparency [187].

Poland's diverse storage portfolio demands tailored MMV. For onshore storage sites, particularly those near densely populated areas, noninvasive monitoring techniques such as satellite-based interferometric synthetic aperture radar (InSAR) and time-lapse seismic surveys are crucial to detect subtle surface deformations and track the migration of CO_2 plume [171]. Meanwhile, offshore storage projects, especially in ecologically sensitive environments, rely on autonomous underwater vehicles (AUVs) equipped with real-time geochemical sensors and sub-bottom profilers to continuously assess storage integrity and detect potential leaks [188]. To monitor casing corrosion in legacy wells, use of electromagnetic field are one of the new ideas that have been developed recent years [189].

To improve detection sensitivity and predict long-term CO_2 behavior, Poland's MMV systems could integrate advanced analytics, including AI-driven plume modeling and machine learning algorithms for anomaly detection. Drone-based soil CO_2 flux measurements and distributed sensor networks provide complementary data streams that, when integrated through centralized data platforms, improve real-time monitoring [190]. This multisensor integration aligns with the EU CO_2 storage directive, which mandates annual leakage rates below 0.01%, ensuring compliance while allowing proactive risk mitigation and rapid response mechanisms in case of unexpected events.

Poland's geological storage outlook focuses mainly on depleted hydrocarbon fields and deep saline aquifers. Legacy sites such as the Barnówko-Mostno-Buszewo (BMB) field offer the advantage of pre-existing well logs and seismic data, potentially reducing MMV costs. Conversely, greenfield sites in the Carpathian Foredeep require preinjection characterization, including 3D seismic mapping and noble gas isotope profiling, to establish accurate baseline conditions and set precise leakage detection thresholds. The Polish Geological Institute (PGI) estimates that MMV systems could account for 15–20% of total storage costs, underscoring the need for cost-efficient innovations in sensor technology and data processing [191].

Beyond technical considerations, robust MMV frameworks are a cornerstone of the evolving regulatory landscape in Poland. The legal framework for CCUS requires continuous monitoring and risk management protocols to ensure long-term storage security. Recent regulatory advances indicate a shift toward hybrid MMV networks that combine state-managed sensors with independent third-party audits [179]. Such redundancies not only strengthen regulatory compliance with EU standards but also enhance public confidence by ensuring transparent and accountable oversight.

7.5 Public Engagement and Social Acceptance

Figure 11 proposes that the successful implementation of carbon storage projects is highly dependent on fostering public trust, social acceptance, and stakeholders' engagement, which vary significantly between different regions. In Poland, public participation faces unique challenges due to the country's historical dependence on coal and fossil fuels, the economic structures of energy-dependent communities, and the broader socio-political landscape. Beyond technical and economic feasibility, building trust and securing societal support are crucial in determining the viability of CCS deployment. As a member of the European Union, Poland must also align its public communication strategies with EU-wide transparency standards and stakeholder participation frameworks [192, 193].

One of the key factors influencing public engagement in Poland is the direct involvement of local stakeholders in decision-making processes (Fig. 11). Studies, including the EU FP7 SiteChar project, have demonstrated that proactive engagement strategies, such as social site characterization and early public consultations, significantly contribute to community trust and project acceptance [194, 195]. Economic benefits and risk communication play a central role in shaping public perception, with local communities more likely to support CCS projects when they see clear advantages in terms of job creation, energy security, and environmental benefits. Transparent information dissemination and direct involvement of community representatives have been shown to improve public confidence in CCS technologies [192, 193].

Trust in government and institutions is another significant determinant of public attitudes toward CCS in Poland. Unlike in some other regions, Polish communities exhibit a relatively high level of trust in local government, which, when combined with strong governmental support and clear communication, facilitates public acceptance [195]. However, public participation strategies must extend beyond passive information sharing to include active participation, where communities are empowered to voice concerns and shape project outcomes. Equally important is the need for a risk management framework. By focusing on stringent safety measures, the integrity of the cap rock and the continuous monitoring of CO_2 storage sites, policymakers can alleviate concerns about leakage and other potential risks. Transparent safety protocols reinforce public confidence and demonstrate commitment to environmental and human safety standards [196].

Table 1 outlines that public engagement in CCS projects across other countries highlights both similarities and contrasts with the Polish experience. Procedural and distributional justice, trust in stakeholders and institutions, and public knowledge of CCS have been identified as key factors shaping acceptance in transnational studies in Belgium, France, Greece, Italy, Norway, Turkey and the United Kingdom [197]. Unlike in Poland, where local economic benefits tend to be the primary driver of acceptance, international studies suggest that fairness in decision-making processes and equitable distribution of risks and benefits significantly impact public attitudes. In addition, in the United States, public support for CCS projects is shaped by perceptions of both technical and social risks, as well as confidence in environmental regulations. Interestingly, the 'Not-in-My-Backyard' (NIMBY) phenomenon, a common challenge in European contexts, is less pronounced in the US, indicating a different public attitude toward the localization of CCS infrastructure [198].

Despite regional variations, common concerns about CCS persist in Europe (Table 1). Studies from the UK, the Netherlands, Germany, Belgium, Spain, and Poland highlight uncertainties surrounding CCS technology and its potential to prolong fossil-fuel dependence [199, 200]. These apprehensions persist even in the presence of additional scientific information, indicating that traditional communication strategies

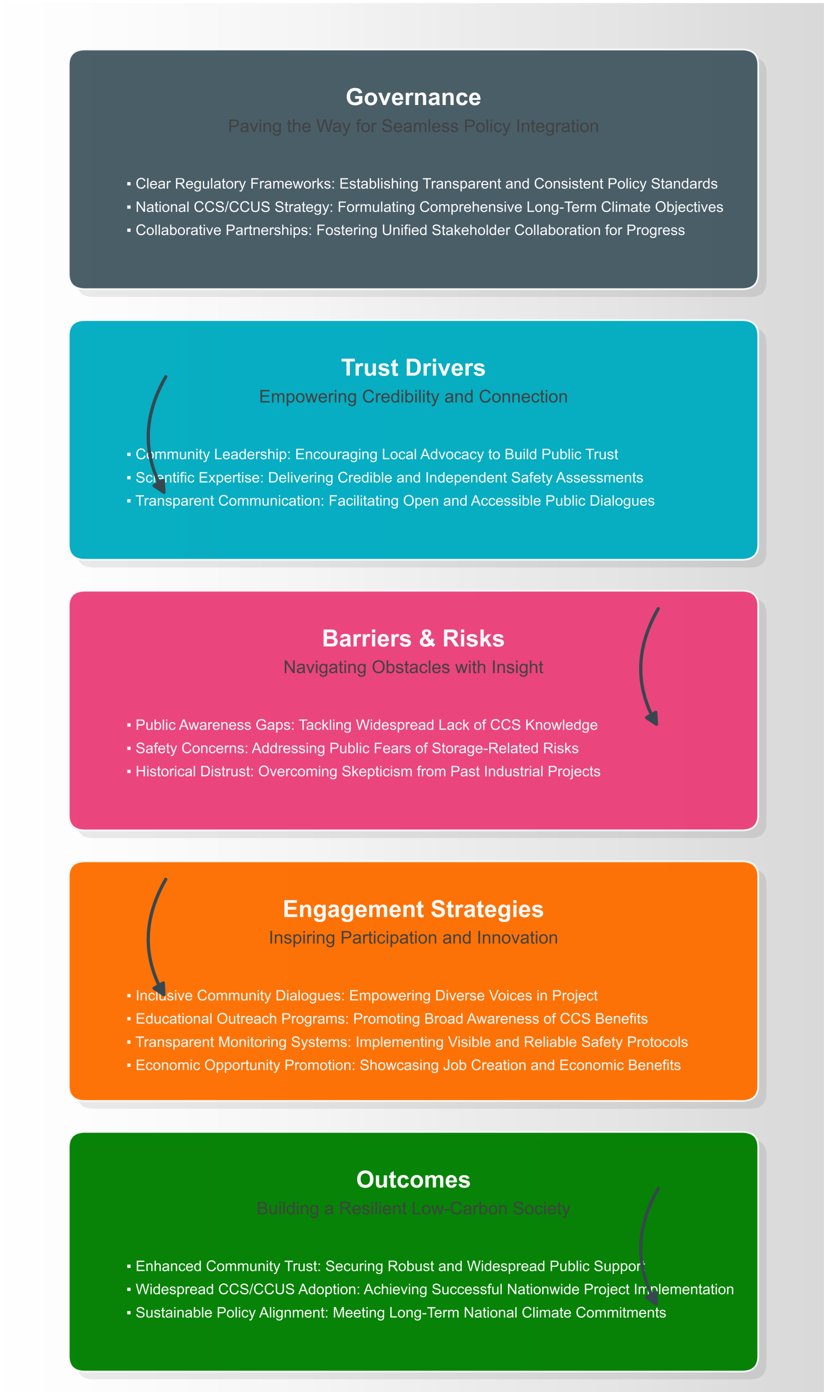

Figure 11: Framework for establishing public trust and stakeholder engagement in CCUS Implementation in Poland. At its core, the framework highlights governance structures that lay the groundwork for transparent and consistent policy formation, which is vital for addressing regulatory challenges and aligning with national climate strategies. Central to the framework are trust drivers, which focus on building robust community confidence through active local leadership and transparent communication. By leveraging scientific expertise to ensure safety and reliability, these trust drivers become instrumental in gaining public support. Recognizing barriers and risks, the framework proactively addresses public concerns and perceptions. It highlights the importance of bridging awareness gaps, mitigating safety fears, and rectifying historical distrust, ensuring a holistic approach to overcoming societal skepticism. Engagement strategies play a pivotal role, emphasizing inclusive community dialogues and educational outreach programs. Through transparent monitoring systems and promoting economic opportunities, these strategies empower citizens to participate in CCUS initiatives, fostering collaboration and innovation. The anticipated outcomes project a vision where enhanced community trust and acceptance lead to the widespread adoption of CCUS technologies. By meeting sustainable policy alignment and achieving national climate commitments, Poland is positioned to transition towards a resilient, low-carbon society, ensuring long-term ecological and economic benefits.

may be insufficient in addressing public skepticism. To improve engagement, it is necessary to tailor public outreach initiatives to specific local contexts, ensuring that communities receive information that is relevant, accessible, and directly applicable to their concerns [201][202].

Table 1: Comparative Analysis of Public Perception and Engagement in CCS Projects: Poland vs. Other Countries

Factor	Poland	Other Countries
Local Stakeholder Involvement	Essential for trust and acceptance. Poland's coal-dependent regions (e.g., Silesia) require active engagement to address fears of economic decline and job losses. Limited efforts to date have resulted in skepticism, especially for onshore storage near communities. Offshore storage discussions are nascent, with less direct stakeholder involvement due to remoteness.	Varies widely. In Spain, proactive engagement with local stakeholders improved acceptance of CCS projects. In Germany, insufficient involvement led to resistance against onshore storage (e.g., Barendrecht project cancellation in 2010). Norway's offshore Sleipner project benefits from stakeholder buy-in tied to national climate goals and maritime expertise.
Public Perception and Communication	Economic benefits (e.g., job preservation in coal regions) and safety assurances are key to gaining support. However, Poland's coal-centric identity fosters skepticism about CCS as a "temporary fix." Onshore storage faces more scrutiny due to proximity risks, while offshore storage is less understood but perceived as safer. Public campaigns are limited, hindering positive perception.	Perceptions vary by context. Australia's governmental and industry backing (e.g., Gorgon project) has fostered optimism about CCS as a climate solution. France shows skepticism due to environmental risks, while Norway's offshore CCS (e.g., Sleipner, Snøhvit) enjoys support due to effective communication of benefits and safety, aligning with climate leadership.
Trust in Government and Institutions	High trust in local government aids acceptance, but national distrust—rooted in historical political challenges—undermines broader support. Poland's slow CCS policy development (e.g., delayed EU CCS Directive adoption) fuels uncertainty, especially for onshore projects. Offshore storage is less contentious due to fewer institutional touchpoints with communities.	Trust shapes outcomes. Canada's high trust in regulators supports CCS acceptance (e.g., Quest project). In the Netherlands, lower trust in institutions has fueled opposition (e.g., Barendrecht). Norway's trusted governance and expertise in offshore operations bolster public confidence in CCS as a viable solution.

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Factor	Poland	Other Countries
Procedural and Distributional Justice	Less prominent in Poland's discourse, overshadowed by economic survival and energy security concerns. Fairness in decision-making is rarely highlighted, with top-down approaches dominating. This gap risks alienating communities, particularly for onshore storage, where benefits and risks are unevenly distributed.	Critical in many countries. In the Netherlands, perceived unfairness in decision-making processes led to opposition to onshore storage. Canada emphasizes equitable benefit distribution (e.g., tax incentives, local jobs), enhancing acceptance. Norway's transparent offshore CCS policies align with justice principles, boosting public support.
Common Concerns	Fears of CO_2 leakage (especially onshore) and prolonged fossil fuel reliance dominate. Poland's coal-heavy energy mix (over 70% of electricity in 2022) amplifies concerns that CCS delays renewable transitions. Offshore storage raises fewer immediate concerns due to isolation, but marine ecosystem impacts are noted. Transparent risk communication is lacking.	Shared across Europe. Germany's opposition to onshore storage stems from leakage fears and fossil fuel lock-in concerns, halting projects like Ketzin. Norway mitigates similar concerns for offshore storage through rigorous monitoring (e.g., Sleipner's 25+ years of safe operation), aligning CCS with climate goals and reducing public apprehension.
Place Factors	Economic benefits drive support in coal regions like Silesia, where CCS could sustain jobs. Onshore storage faces resistance due to land use conflicts and proximity to populated areas. Offshore storage in the Baltic Sea is geologically feasible but less prioritized, reducing local contention. Socio-political ties to coal shape a pragmatic yet cautious stance.	Context-specific. In Canada, fossil fuel regions support CCS for economic continuity (e.g., Alberta's projects). Germany's onshore storage faces land use opposition, while offshore options gain traction in the North Sea. Norway leverages its maritime heritage and sparse population to favor offshore CCS, aligning with local benefits and climate policy.
Environmental Impact Perception	Mixed views: CCS is seen as an emissions reduction tool, but onshore risks (e.g., groundwater contamination) and offshore risks (e.g., Baltic Sea ecosystem impacts) spark concern. Offshore storage is preferred due to distance from communities, though awareness of its environmental footprint is low. Poland's industrial pollution history heightens scrutiny.	Diverse perceptions. Norway views offshore CCS as environmentally benign, supported by decades of safe operation. The UK favors offshore storage (e.g., Endurance aquifer) over onshore due to lower perceived risks. Germany's onshore storage faces backlash over potential ecological damage, reflecting a cautious environmental ethos post-industrial legacy.

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Factor	Poland	Other Countries
Technological Trust	Low trust in CCS technology, especially onshore, due to limited awareness and past industrial accidents (e.g., coal mine disasters). Offshore storage garners slightly more confidence due to perceived isolation and less direct community impact. Poland's lack of operational CCS projects (e.g., stalled Bełchatów pilot) reinforces doubts.	Varies by expertise. Norway and Canada trust CCS technology, backed by successful projects (e.g., Sleipner, Boundary Dam). Germany distrusts onshore storage tech, leading to cancellations, while offshore is more accepted in maritime nations like the UK and Norway, where technical competence aligns with public confidence.
Regulatory Framework	Developing and incomplete. Poland adopted the EU CCS Directive (2009) but lacks specific onshore/offshore regulations, delaying projects like Bełchatów (cancelled 2013). This ambiguity fuels public uncertainty, particularly for onshore storage near communities. Offshore regulation is even less defined, limiting progress in the Baltic Sea.	More advanced elsewhere. Norway's robust offshore framework (e.g., 1996 Sleipner start) supports public confidence. The UK has clear offshore CCS policies (e.g., CCUS Cluster Sequencing), while onshore lags. The US varies by state, with Texas offering strong onshore regulations. Regulatory clarity typically enhances acceptance.
Media Influence	Media frames CCS around energy security and coal preservation, but often highlights onshore risks (e.g., leakage). Limited positive coverage of CCS successes (domestic or global) sustains skepticism. Offshore storage receives less attention, leaving perceptions unformed but less negative.	Significant impact. Australia's media promotes CCS as a climate fix (e.g., Chevron Gorgon), boosting support. Germany's negative onshore coverage (e.g., framing as risky) drives opposition. Norway's media ties offshore CCS to national pride and climate leadership, fostering a positive public view.
Cultural and Historical Context	Poland's coal-centric culture (e.g., "black gold" legacy) sees CCS as a lifeline for jobs, yet fears of repeating industrial pollution (e.g., 1970s smog crises) persist, especially for onshore storage. Offshore storage lacks cultural resonance but avoids historical baggage, making it less contentious.	Shapes attitudes. Norway's maritime tradition supports offshore CCS acceptance. Germany's anti-nuclear and industrial skepticism spills into onshore CCS resistance. Canada's pragmatic fossil fuel culture views CCS as a necessary evolution, balancing economic and environmental priorities.

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Factor	Poland	Other Countries
Education and Awareness	Low CCS awareness due to minimal public education efforts. A 2019 EU survey showed Poland lagging in climate tech knowledge, increasing onshore storage fears (e.g., leakage). Offshore storage is poorly understood but less feared due to remoteness. Lack of outreach hinders acceptance.	Varies by effort. The UK and Norway run awareness campaigns (e.g., CCS Explained) to improve offshore acceptance. Germany's high awareness doesn't translate to support due to risk focus. Canada's education ties CCS to economic benefits, reducing skepticism in fossil fuel regions.
Economic Dependence on Fossil Fuels	Poland's 70%+ coal reliance (2022) makes CCS appealing to decarbonize without abandoning coal, yet sparks fears of delaying renewables. Onshore storage is tied to coal regions, amplifying economic stakes. Offshore storage is less linked to immediate economic needs, reducing its priority.	Influences perception. Canada and Australia support CCS in sustaining fossil fuel economies (e.g., Alberta and Queensland). Denmark, with a renewable focus, views CCS skeptically as a fossil fuel crutch. Norway balances oil/gas wealth with climate goals, favoring offshore CCS as a dual-purpose solution.
Government Policy and Support	Tepid support, prioritizing coal over climate innovation. Poland's 2030 Energy Policy mentions CCS but lacks funding or firm targets, reflecting ambivalence. This weakens public enthusiasm, especially for onshore projects; offshore remains exploratory (e.g., Baltic potential studies).	Stronger elsewhere. Norway's aggressive CCS policy (e.g., Longship project, $2.4B investment) drives acceptance. The UK backs offshore CCS (e.g., Net Zero Teesside), boosting confidence. Germany's policy uncertainty stalls onshore progress, while the US offers tax credits (e.g., 45Q) for onshore CCS, enhancing support in key states. Denmark Energy Agency with state funding has allocated in total DKK 38 billion for a CCS pool.
Community Engagement Strategies	Top-down and limited, lacking transparency. Poland's approach (e.g., Bełchatów's failed outreach) alienates communities, especially for onshore storage. Offshore engagement is minimal due to early-stage development, leaving potential untapped.	More effective elsewhere. Spain and Canada use participatory methods (e.g., town halls, co-design) to improve acceptance. Norway engages communities on offshore CCS via national climate narratives, building support. Germany's lack of engagement exacerbated onshore opposition (e.g., Barendrecht in 2010).

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Factor	Poland	Other Countries
Risk Perception (Onshore vs. Offshore)	Onshore storage is riskier in public eyes—fears of leakage, seismicity, and groundwater issues dominate due to proximity (e.g., Silesia's dense population). Offshore storage in the Baltic is considered safer due to its distance and natural containment, although ecological risks are noted.	Consistent trends. Germany rejects onshore storage due to similar risks (e.g., the Jänschwalde cancellation), favoring offshore storage. Norway and the UK see offshore as low-risk (e.g., North Sea successes), bolstered by monitoring. The US varies—Texas accepts onshore risks for economic gain, while others resist.

Local stakeholder involvement plays a crucial role in Poland, where trust and direct engagement are essential for public acceptance [193, 192, 195]. This contrasts with other regions, where the importance of stakeholder participation varies depending on national policies and public attitudes [194, 197] (Table 1). Public perception in Poland is strongly shaped by economic benefits and risk communication strategies, emphasizing the need for transparent discussions on CCS technology and its socio-economic implications [193, 195].

Another significant factor that distinguishes Poland from other countries is the level of trust in its government and institutions (Table 1). Polish communities generally exhibit high trust in local authorities, which can facilitate public acceptance of CCS projects if governments maintain open and transparent communication [195]. In contrast, other countries demonstrate varying levels of confidence in their regulatory frameworks, which influences the effectiveness of engagement strategies [200]. Procedural and distributional justice, while less emphasized in Poland, has been shown to have a significant impact on public acceptance in other European nations [194].

Common concerns about CCS, such as uncertainty and its potential to perpetuate fossil-fuel dependence, persist across Europe, indicating a broader need for targeted communication and educational initiatives [199]. Furthermore, place-specific factors also shape CCS acceptance, with local economic benefits being a primary driver of support in Poland, whereas in other regions, socio-political contexts and broader sustainability policies play a more dominant role [201, 198].

An effective public engagement strategy for CCS in Poland must begin with transparent, science-based communication that explains the entire CCS process, from CO_2 capture to transportation and long-term geological storage. Public education campaigns using traditional media and digital platforms can help demystify technology for non-expert audiences and counteract misinformation [203, 204]. In addition, participatory decision-making must be prioritized, particularly in regions where economic dependence on traditional energy sources remains strong. Public consultations, community meetings, and co-designed planning processes can help integrate local voices into project development, addressing concerns about environmental risks and economic impacts while also emphasizing the long-term benefits of CCS for energy security and job creation in emerging green industries [195, 205].

To further strengthen public confidence, Poland should align its CCS strategies with EU directives and best practices. The European Union has established benchmarks for stakeholder participation and transparent reporting in CCS projects, including through initiatives such as the *Net Zero Industry Act*. By adopting these standards, Poland can benefit from the experiences of other EU member states and develop a robust framework for implementing sustainable CCS [197].

Ultimately, as reviewed in Table 1 and outlined in Figure 11, public acceptance requires an inclusive, transparent, and participatory approach. Well-informed and actively engaged communities do not merely accept CCS projects; they become partners in their development, driving regulatory support and attracting financial investments. In a policy landscape where public opinion significantly influences decision-making, a well-structured engagement strategy can accelerate the adoption of CCS technologies, ensuring that Poland's transition to a low-carbon future is both socially sustainable and widely supported. Overcoming the public engagement bottleneck will require a combination of clear scientific communication, participatory governance, strong risk management, and alignment with EU regulatory frameworks, all of which are necessary to make CO_2 storage projects viable both economically and socially across the country.

7.6 Closing Observations

Poland's onshore CO_2 storage potential remains pivotal to developing a robust CCUS value chain, particularly while offshore constraints and cross-border conflicts in the Baltic Sea region persist. Prioritizing depleted hydrocarbon reservoirs and saline aquifers, located near industrial emitters to facilitate hub formation, is essential for ensuring storage capacity, injectivity, and containment—the core pillars of geological carbon sequestration. However, the economic feasibility of these initiatives hinges on overcoming high capture, transport and infrastructure costs, necessitating a clear and comprehensive regulatory framework for both onshore and offshore sites.

The provisional storage capacity estimates presented in this synthesis review underscore Poland's subsurface geological potential but carry significant uncertainty over wide probability percentiles due to reliance on static theoretical methods. Advanced dynamic reservoir simulations, informed by geophysical, geological, geochemical, geomechanical, and hydromechanical studies, alongside drilling and testing, are imperative to validate storage structures, assess rock behavior during injection, and ensure operational safety. These efforts must be underpinned by enhanced research and development (R&D) and strengthened academia-industry partnerships, as outlined in [16].

By 2030, securing access to external CO_2 storage reservoirs, such as those in the North Sea [16, 161], is critical to accommodate emissions from Poland's high-priority industrial sectors. This strategy requires robust governmental and commercial agreements to enable cross-border storage solutions. Concurrently, preparatory and pilot projects must commence immediately to lay the groundwork for large-scale deployment by 2030–2040. The question of whether depleted hydrocarbon reservoirs, offering higher storage readiness levels, should be prioritized over saline aquifers or hybrid systems requires detailed techno-economic analyses and comprehensive subsurface characterization.

Pilot projects targeting onshore depleted hydrocarbon reservoirs and high-SRL saline aquifers should be launched by 2030 to address technical and logistical challenges as a prerequisite for large-scale sequestration initiatives in the next decade, for instance, in Lower Jurassic saline structures. These pilot initiatives require a steady CO_2 supply from emerging capture projects and the development of marine terminals to support integration.

Conclusions

This study aimed to establish a blueprint for lower-maturity and emerging CCS regions by developing a standardized CO_2 storage assessment methodology, enabling synthesis and high-level prioritization of sequestration sites to align with global decarbonization objectives. By integrating diverse data sources, including geological surveys, industrial reports, and policy frameworks, it provides a multidisciplinary framework that incorporates critical elements into a cohesive, high-level evaluation of CO_2 storage potential applicable to diverse global contexts, with Poland's enormous subsurface resources as an example.

As the EU's fourth-largest emitter (~11.2% of EU27 greenhouse gas emissions in 2022), Poland must decarbonize its carbon-intensive industries, requiring CCUS solutions. This synthesis review indicates that Poland's geological CO_2 storage potential, initially estimated at approximately 15 Gt (14.3 Gt in deep saline aquifers, 1 Gt in depleted hydrocarbon reservoirs), is evaluated to 10.2–12.7 Gt at storage readiness levels (SRL 1–2) later on, and recently refined by a European research consortium to 8.9 Gt at SRL 2–3, encompassing saline aquifers and depleted hydrocarbon reservoirs. This high-level assessment of theoretical capacity in onshore and offshore reservoirs can positions Poland as a leading CCUS hub in the region. Diverse storage options, encompassing onshore deep saline aquifers and sedimentary basin structures near major emitters within Poland, alongside Baltic Sea Cambrian reservoirs and repurposed hydrocarbon fields like Barnówko-Mostno-Buszewo, provide flexible, regionally tailored pathways to meet both near-term and long-term storage needs.

Advancing Poland's CO_2 storage potential to higher SRLs and practical storage capacity requires integrating diverse and newly acquired datasets and localized thermo-hydro-mechanical-chemical (THMC) factors. Current assessments face challenges, including sparse data and restricted research access, which impede basin-scale and site-specific analyses. Data deficiencies and inadequate subsurface validation diminish confidence in CO_2 storage capacity estimates, impeding strategic investment in Poland's large-scale deployment. Stakeholders must prioritize comprehensive data acquisition, including advanced geophysical surveys and targeted drilling, coupled with robust modeling, to enhance assessment reliability and foster collaborative partnerships, thereby enabling a scalable, economically viable CCUS value chain.

Infrastructure and policy flexibility are crucial components in the advancement of Poland's geological storage initiatives. Developing robust domestic infrastructure, coupled with fostering cross-border collaboration, is vital for establishing a CO_2 transport network that effectively minimizes logistical costs and streamlines connectivity between emission sources and storage sites. Recent amendments to Poland's Geological and Mining Law, which can eventually translate to onshore storage permits, introduce additional cost-efficient options, particularly benefiting industrial clusters in the south. This regulatory advancement is poised to diminish existing barriers and expedite deployment. Targeted investments and financial incentives, supported by sustained EU funding are expected to enable CO_2 reductions in the next decade via carbon sequestration. These investments not only promise significant emission reductions but are also expected to safeguard jobs, contributing to economic stability.

Public acceptance and stakeholder engagement are fundamental to the success of large-scale deployment strategies. Enhancing transparency through advanced MMV frameworks and community-led monitoring initiatives is crucial for garnering domestic support for geological storage and CCUS projects. These efforts will not only build public trust but also reduce regulatory uncertainties, ultimately paving the way for a more resilient and sustainable decarbonization pathway.

Appendix

Table 2: A list of potential CO_2 storage sites identified in Poland ([86, 106]), categorized into "Deep Saline Aquifers" (DSA) and "Hydrocarbon Fields" (HF) (refer to Figure 9). The storage sites are ranked by storage capacity from highest to lowest for each category. SRL stands for Storage Readiness Level (refer to Figure 5). All listed items are daughter units, which are specific structural and stratigraphic traps contained within a storage unit. By definition, depleted hydrocarbon fields qualify as daughter units, utilizing their established geological structures to store CO_2 safely.

Storage Name	Storage Type	Location	SRL	Capacity [Mt]
Gostynin	DSA	Onshore	2	514
Suliszewo	DSA	Onshore	2	509
Wojszyce	DSA	Onshore	3	342
Wyszogród	DSA	Onshore	2	315
Konary J	DSA	Onshore	2	282
Jeżów T	DSA	Onshore	2	277
Rokita	DSA	Onshore	2	264
Debrzno	DSA	Onshore	2	246
Huta Szklana	DSA	Onshore	2	224
Sochaczew J	DSA	Onshore	2	222
Sierpc K	DSA	Onshore	2	212
Sochaczew K	DSA	Onshore	2	206
Choszczno	DSA	Onshore	2	205
Wierzchowo	DSA	Onshore	2	194
Bielsk-Bodzanów	DSA	Onshore	2	194
Konary T	DSA	Onshore	2	182
Jeżów J	DSA	Onshore	2	166
Niecka Poznańska (G-U-B-P)	DSA	Onshore	2	165
Grudziądz	DSA	Onshore	2	157
Sierpc J	DSA	Onshore	2	152
Kamionki J	DSA	Onshore	2	149
Marianowo J&T	DSA	Onshore	3	129
Budziszewice-Zaosie	DSA	Onshore	2	107
Radnica	DSA	Onshore	2	87
Dzierżanowo	DSA	Onshore	2	84
Lutomiersk	DSA	Onshore	2	78
Trześniew	DSA	Onshore	2	78
Kliczków J	DSA	Onshore	2	77
Bodzanów	DSA	Onshore	2	77
Kowalowo	DSA	Onshore	2	76
Husów-Albigowa-Krasne	DSA	Onshore	3	63
Bielsk	DSA	Onshore	2	63
Trzebież	DSA	Onshore	2	61
Turek	DSA	Onshore	2	61
Wartkowice	DSA	Onshore	2	53
Szubin	DSA	Onshore	2	47
Tuszyn	DSA	Onshore	2	41

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Storage Name	Storage Type	Location	SRL	Capacity [Mt]
Radlin	DSA	Onshore	3	17
Zat Gdowska	DSA	Onshore	2	15
Skoczów-Czechowice	DSA	Onshore	2	14
Oświno K	DSA	Onshore	2	13
Grobla	DSA	Onshore	2	13
Żyrów	DSA	Onshore	2	11
J_15_POL_K	DSA	Offshore	2	102
MBu_28_POL_K	DSA	Offshore	2	52
J_06_POL_H	DSA	Offshore	2	48
J_14_POL_K	DSA	Offshore	2	39
MBu_23_POL_K	DSA	Offshore	2	36
MBu_19_POL_K	DSA	Offshore	2	27
Przemyśl	HF	Onshore	3	370
Żuchlów	HF	Onshore	3	138
Brońsko	HF	Onshore	3	91
Bogdaj-Uciechów	HF	Onshore	3	88
Jarosław	HF	Onshore	3	36
Kościan S	HF	Onshore	3	35
BMB	HF	Onshore	3	30
Paproć	HF	Onshore	3	27
Wilków	HF	Onshore	3	23
Tarnów (miocen)	HF	Onshore	3	15
Czeszów	HF	Onshore	3	10
Lubiatów	HF	Onshore	3	10
Paproć W	HF	Onshore	3	10
Grodzisk_Wlkp.	HF	Onshore	3	9
Lubaczów (J)	HF	Onshore	3	9
Brzostowo	HF	Onshore	3	8
Góra	HF	Onshore	3	8
Łąkta	HF	Onshore	3	6
Niepołomice	HF	Onshore	1	6
Węglówka	HF	Onshore	3	4
Kamień Pomorski	HF	Onshore-Offshore	3	3
Buk	HF	Onshore	3	1
Dzieduszyce	HF	Onshore	3	1
Osobnica	HF	Onshore	3	1
Radoszyn	HF	Onshore	3	1
Wysoka Kamieńska	HF	Onshore	3	1
Nosówka	HF	Onshore	3	0.5
B 3	HF	Offshore	3	11
B 8	HF	Offshore	3	8

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