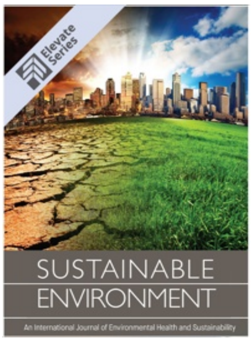

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Protocol for modeling integrated CO_2 geological storage hubs in offshore environments

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ABSTRACT

The development of effective protocols for Carbon Capture and Storage (CCS) is essential to advancing climate change mitigation strategies. This paper presents an integrated protocol tailored for evaluating the feasibility and implementation of offshore CO_2 storage hubs, incorporating the TERES Protocol (Technological, Environmental, Regulatory, Economic, and Social dimensions). The methodology integrates expert-based risk weighting, multidimensional indicators, and comparative benchmarking with international CCS initiatives. By applying this framework to the Merluza Field in the Santos Basin, the study highlights how comprehensive risk assessment and multi-dimensional analysis can guide successful CCS projects. Key findings emphasize the importance of leveraging existing infrastructure to reduce costs, the need for rigorous well integrity measures, and continuous regulatory alignment. The application of the protocol revealed a predominance of high-priority risks in regulatory, technological, and economic dimensions, reflecting the challenges of CCS deployment in emerging contexts. The risk assessment, employing a weighted scoring system, identified well integrity and infrastructure suitability as top priorities, requiring focused mitigation strategies. The study underscores the value of integrating historical data and advanced modeling techniques for accurate reservoir behavior predictions and economic planning. Additionally, stakeholder engagement and robust environmental monitoring were emphasized to ensure minimal ecological impact and foster public trust. The protocol demonstrated adaptability for application in diverse geological and infrastructural contexts, supporting the scalability of CCS initiatives globally. This study provides a reference model that promotes safe, economically viable, and socially responsible CO_2 storage solutions, contributing to long-term sustainability and alignment with climate targets.

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CO_2 geological storage; feasibility carbon capture and storage protocol; offshore hubs; Santos Basin; Carbon capture and storage technology

1. Introduction

The urgency of addressing climate change has accelerated the development of Carbon Capture and Storage (CCS) as a relevant technology for reducing atmospheric CO_2 emissions (Metz et al., 2005; Oyewole et al., 2023). CCS encompasses a suite of technologies designed to capture CO_2 from industrial sources, such as power plants, cement factories, and refineries (Cachola et al., 2023; Heuberger et al., 2017; Sood & Vyas, 2017). Once captured, the CO_2 undergoes compression and is transported—typically via pipelines or ships—to designated geological formations, such as depleted oil and gas reservoirs or deep saline aquifers, for secure, long-term storage (Cao et al., 2020; Rasool et al., 2023). This process mitigates emissions by isolating CO_2 from the atmosphere over geological time scales, leveraging the natural sealing properties of caprocks to ensure containment (Liu et al., 2023; Metz et al., 2005). Beyond emissions reduction, CCS contributes to a circular carbon economy when integrated with carbon capture and utilization (CCU) systems, enabling the repurposing of captured CO_2 in the production of fuels, chemicals, and materials (Cachola et al., 2023; Jiang & Ashworth, 2021; Jiang et al.,

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2020). Such applications align with principles of resource efficiency and industrial sustainability. More broadly, CCS has gained increasing recognition as a cornerstone of net-zero strategies, especially for hard-to-abate sectors such as cement, steel, refining, and petrochemicals. Its scalability and compatibility with existing industrial processes make it uniquely suited to deliver emissions reductions at the depth and speed required for mid-century climate targets (Bui et al., 2018; Haszeldine et al., 2018). As one of the few scalable technologies capable of achieving substantial decarbonization across various sectors, CCS plays an essential role in global efforts to meet climate targets, including those set by the Paris Agreement (M. Ciotta et al., 2020; Ghazali & Zahid, 2022).

The primary geological formations utilized for CO_2 storage are depleted oil and gas reservoirs and deep saline aquifers, each offering distinct advantages and challenges (Metz et al., 2005; Olawoyin et al., 2016; Rasool et al., 2023). Depleted oil and gas reservoirs are particularly favorable due to their proven ability to trap fluids over geological timescales securely (Hannis et al., 2017; Wei et al., 2023). This reliability stems from their well-characterized structural and sealing properties, which significantly mitigate uncertainties related to long-term storage integrity (Godec et al., 2011; Hannis et al., 2017). Additionally, these reservoirs often feature pre-existing infrastructure—such as wells, pipelines, and platforms—that can be retrofitted for CO_2 injection and monitoring (Sachde et al., 2022). This reuse of assets not only reduces capital expenditures (CAPEX) and operational costs but also accelerates project timelines by leveraging established supply chains and logistical networks (Pearson et al., 2019; Tomić et al., 2018). Saline aquifers, while not associated with existing infrastructure, are widespread and offer substantial storage capacities suitable for sequestering CO_2 from multiple sources over extended periods (Delshad et al., 2022).

Offshore CCS hubs, exemplified by the proposed Merluza CCS Hub, represent a transformative approach to centralized CO_2 management, offering both efficiency and scalability in addressing global emissions (Guler et al., 2018). These hubs are strategically designed to collect CO_2 from diverse industrial sources, both onshore and offshore, and store it in a single, meticulously characterized geological site (Dudu et al., 2020). By consolidating CO_2 from multiple emitters, they streamline logistics, reduce operational complexities, and maximize storage efficiency (Guler et al., 2018). Offshore environments, particularly depleted oil and gas reservoirs such as the Merluza Field in the Santos Basin, stand out as optimal candidates for CCS hubs (M. R. Ciotta & Tassinari, 2020). Their geographic isolation from populated areas minimizes potential environmental and social conflicts, while their significant storage capacities provide long-term solutions for CO_2 sequestration (Tomić et al., 2018). The geological characteristics of depleted reservoirs—proven sealing properties, well-understood subsurface conditions, and historical data—enhance the predictability and security of CO_2 containment over extended periods (Le Goff et al., 2021). Moreover, one of the most compelling advantages of offshore CCS hubs is the opportunity to repurpose existing oil and gas infrastructure. Platforms, pipelines, and wells can be retrofitted for CO_2 injection and monitoring, significantly reducing capital expenditures (CAPEX) and operational costs (OPEX). This reuse accelerates project deployment and supports a just transition for regions historically reliant on fossil fuel industries, enabling them to pivot toward sustainable, low-carbon technologies (Pearson et al., 2019).

Previous studies on CO_2 storage protocols have made significant progress in characterizing geological suitability and assessing long-term containment (Romanak & Dixon, 2022). Initiatives such as the IEAGHG Storage Site Characterisation guidelines, the CarbonSAFE program in the United States, and the Re-Stream project in Europe have established important methodological references for site selection, monitoring, and infrastructure reuse (DNV, 2021; IEAGHG, 2009; NETL, 2016). However, these approaches often focus on specific technical dimensions and are rarely applied holistically to the offshore context. Moreover, most existing frameworks originate in mature regulatory environments and do not fully address the institutional and socio-environmental uncertainties typical of emerging economies. This is particularly relevant in the Brazilian context, where offshore geological potential is high, but regulatory structures, market incentives, and public awareness of CCS remain underdeveloped. These gaps highlight the need for integrative tools that can support project planning and policy alignment under conditions of regulatory and informational asymmetry.

This study aims to bridge that gap by introducing the TERES Protocol, a fully integrated, risk-weighted methodology that captures the complex interdependencies among technical feasibility, environmental safeguards, regulatory readiness, economic viability, and stakeholder engagement. Its application to the Merluza Field illustrates how such a protocol can support decision-making for offshore CCS deployment under conditions of regulatory and market immaturity, contributing to both academic knowledge and policy development in Brazil and beyond.

The success of such hubs depends on the integration of technological, regulatory, economic, social, and environmental dimensions, which form the foundation of the modeling protocol presented. Key considerations include adapting existing infrastructure for CO_2 storage, ensuring regulatory compliance, minimizing environmental impact, and engaging stakeholders to foster public trust. By addressing these interconnected factors through an interdisciplinary approach, the study ensures that offshore CCS hubs are not only technically and economically viable but also sustainable and aligned with global decarbonization goals. This framework highlights the potential of CCS hubs to significantly contribute to climate mitigation efforts, supporting long-term emissions reductions and compliance with international climate targets.

Moreover, this study introduces the first integrated modeling protocol for offshore CO_2 storage in Brazil that combines real field data with a multidimensional, risk-based assessment framework. The TERES Protocol (Technological, Environmental, Regulatory, Economic, and Social) offers a novel approach by incorporating historical reservoir and infrastructure data into a scalable and adaptable methodology that addresses the complexity of offshore CCS deployment. Its application to the Merluza Field exemplifies how technical feasibility, regulatory compliance, and social legitimacy can be jointly evaluated through a single, coherent protocol.

This study is structured as follows. Section 2 presents the integrated methodology and the TERES protocol across technological, environmental, regulatory, economic, and social dimensions, including the weighted risk-prioritization system. Section 3 introduces the Merluza Field case study, describing datasets, reservoir characteristics, and infrastructure context. Section 4 provides the results of risk scoring, hub benchmarking against international projects, and protocol comparison. Section 5 discusses implications, limitations, and the theoretical contribution of the TERES framework. Finally, Section 6 concludes with policy recommendations and future research directions.

2. Methodology

The methodology for developing an integrated protocol for CO_2 storage hubs in offshore environments is structured to comprehensively assess technological, environmental, regulatory, economic, and social dimensions. This multi-faceted approach ensures a robust evaluation of the feasibility, safety, and sustainability of such projects. Drawing on insights from international CCS practices and existing frameworks in Brazil, particularly those involving the Merluza Field in the Santos Basin, the protocol aims to address the unique challenges of offshore CCS implementation while aligning with global decarbonization goals.

2.1. Technological dimension

The technological dimension focuses on evaluating and optimizing the critical stages of CO_2 injection and long-term monitoring. This involves the application of advanced tools and methodologies:

- Reservoir modeling: advanced 3D geological and reservoir simulations are conducted using specialized software (e.g. Leapfrog and Petrel) to analyze subsurface characteristics and predict CO_2 behavior. Data from the PROMAR database, including geological, geochemical, and petrophysical information from nine wells in the Merluza Field, as well as 2D and 3D seismic data, are integrated to create accurate models of the storage site. These models enable dynamic simulations to assess injectivity, capacity, and containment security.
- Infrastructure reuse assessment: the feasibility of retrofitting existing oil and gas infrastructure, such as wells, pipelines, and platforms, is evaluated. This includes assessing material compatibility with CO_2, structural integrity, and system lifespan. Criteria such as the age, condition, and historical performance of infrastructure are incorporated into the assessment. For instance, the reuse of the PMLZ-1 platform, operational from 1993 to 2020, offers potential cost savings and operational efficiencies.
- Monitoring systems: state-of-the-art monitoring technologies, including seismic imaging, pressure sensors, fiber optic sensors, and real-time data acquisition systems, are integrated to track CO_2 plume

migration and detect potential leaks. Emerging tools like autonomous underwater vehicles (AUVs) and drones are considered for continuous inspection of offshore infrastructure.

Uncertainty management is a central aspect of the technological evaluation process within the TERES Protocol. Given the complexity of subsurface systems, factors such as reservoir heterogeneity, fault behavior, and caprock integrity are assessed using a combination of expert judgment, historical data confidence, and probabilistic interpretation of seismic and well log datasets. These inputs feed into the weighted risk matrix via qualitative uncertainty modifiers, allowing the protocol to reflect not only the severity of technical risks but also the confidence level associated with each assessment. This is particularly relevant for offshore fields like Merluza, where operational history can help constrain, but not eliminate, geological uncertainty. Specific manifestations of these uncertainties are addressed in Section 4.2.1.

2.2. Environmental dimension

The environmental dimension assesses potential ecological impacts and ensures the sustainability of CCS operations in offshore settings:

- Baseline environmental studies: comprehensive studies document the current state of marine ecosystems in the Santos Basin. These benchmarks are relevant for measuring and mitigating potential impacts during CO_2 injection and storage. Parameters such as biodiversity, water chemistry, and sediment composition are analyzed. In Brazil, baseline studies are often derived from the Environmental Impact Assessment and Report (EIA-RIMA), which is a mandatory requirement coordinated by Petrobras before initiating oil and gas production in offshore fields. These studies provide a robust scientific foundation not only for initial licensing, but also for subsequent monitoring, impact forecasting, and adaptive environmental management in CCS projects.
- Impact and risk analysis: advanced models are proposed simulate CO_2 migration and potential leakage paths, focusing on interactions with geological formations. For example, studies of the Merluza Field's Santonian sandstones reveal porosity and permeability values (16% and 19%, respectively) that inform risk mitigation strategies.
- Post-injection monitoring: a long-term monitoring plan should be developed, incorporating environmental tracers, isotopic analysis, and microbial assessments to detect leaks and evaluate the stability of CO_2 storage.
- Sustainability considerations: incorporating findings from studies on the environmental implications of reusing depleted reservoirs, which emphasize that these reservoirs are well-suited for CO_2 retention due to their proven geological stability and minimal ecological impact.

2.3. Regulatory dimension

The regulatory component ensures compliance with local, national, and international standards:

- Regulatory review and alignment: a detailed analysis is conducted to identify relevant regulations and standards governing CCS projects. This includes the guidelines of the Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP), ISO standards (e.g. ABNT NBR ISO 27,914), and the overarching legal framework for CCS in Brazil. Additionally, comparative studies are undertaken to benchmark Brazil's regulatory landscape against global best practices, such as those implemented in the North Sea (e.g. UK CCS Regulatory Framework) and Gulf of Mexico. This comparative approach highlights potential regulatory gaps and areas where international standards can inform improvements in Brazil's CCS governance.
- Permitting and compliance protocols: establishing a roadmap for obtaining necessary permits and aligning project activities with current legal standards. This includes a review of the Brazilian regulatory framework, such as Projeto de Lei 1425/2022 (Marco Regulatório de Captura de Carbono).
- Post-closure care: developing procedures for long-term monitoring and compliance to ensure permanent CO_2 storage and address regulatory requirements for site closure.

2.4. Economic dimension

Economic analysis ensures project viability by assessing:

- CAPEX and OPEX analysis: estimating capital and operational expenditures for retrofitting existing infrastructure and operational processes. The reuse of existing platforms like PMLZ-1 and the 215 km pipeline connecting to the Presidente Bernardes Refinery are factored into cost-saving estimates.
- Revenue potential and funding: evaluating potential revenue from carbon credits and incentives for CO_2 storage, as well as public, private, and hybrid financing models to support the project.
- Economic sensitivity analysis: conducting analyses to understand the impact of variables such as carbon credit prices and market fluctuations on long-term economic sustainability.

2.5. Social dimension

The social dimension focuses on community engagement and socioeconomic impact:

- Stakeholder mapping and public consultation: identifying key stakeholders, including local communities and industrial partners, and conducting public consultations to gather input and build trust. This approach is essential given the offshore location of the Merluza Field, which minimizes direct impacts on populated areas but requires comprehensive community involvement for broader support.
- Socioeconomic benefits: assessing the potential for job creation, technology transfer, and regional economic development. The work emphasizes that CCS projects should be seen as mitigation tools aligned with sustainability goals rather than mere extensions of fossil fuel activities.
- Communication strategy: developing transparent communication plans that provide clear information about project benefits and risks, fostering positive stakeholder relationships.

2.6. Integration of dimensions

The TERES Protocol (Technological, Environmental, Regulatory, Economic, and Social) integrates multi-dimensional assessments through a weighted risk prioritization framework (Figure 1). Each domain contributes to the feasibility and safety evaluation of offshore CO_2 storage hubs, with outputs feeding into a unified risk-informed decision-making process. These five dimensions are interconnected to provide a broad assessment of the CCS hub's feasibility. For example, technological findings inform economic models, while environmental and regulatory analyses guide the development of monitoring and compliance strategies. The use of historical data from previous production and well performance, coupled with current regulatory and socioeconomic analyses, creates a comprehensive protocol adaptable for future projects, aligning with the need for responsible CO_2 storage solutions as outlined by national decarbonization goals.

The integration of the five analytical dimensions within the TERES Protocol responds to an increasing demand in the CCS research community for multiscale and interdisciplinary modeling approaches. Recent studies have highlighted the benefits of coupling reservoir simulations with techno-economic assessments, risk analysis, and even public perception modeling to improve project feasibility and policy alignment (Middleton et al., 2012; Ringrose, 2020; Simon et al., 2021). These efforts demonstrate that the viability of CCS projects extends far beyond geomechanical suitability or storage capacity, requiring robust frameworks capable of evaluating systemic interactions and trade-offs across spatial, temporal, and institutional scales.

For instance, Middleton et al. (2012) developed an integrated modeling framework that links basin-scale CO_2 transport and storage simulations with economic cost functions and infrastructure optimization models, illustrating how network design and policy scenarios interact. Similarly, Simon et al. (2021) proposed a decision-support tool that incorporates technical risks, cost uncertainties, and social acceptance metrics to compare CCS site options. While these models represent major advances in system-level CCS assessment, they often remain focused on specific dimensions or geographic scales. Recent advances in computational modeling further support the refinement of such feasibility assessments. For example, Chandra et al. (2025) developed Fourier Neural Operator surrogates to simulate CO_2 plume migration in realistic geological settings, providing a fast and accurate tool for preliminary site screening (Chandra et al.,

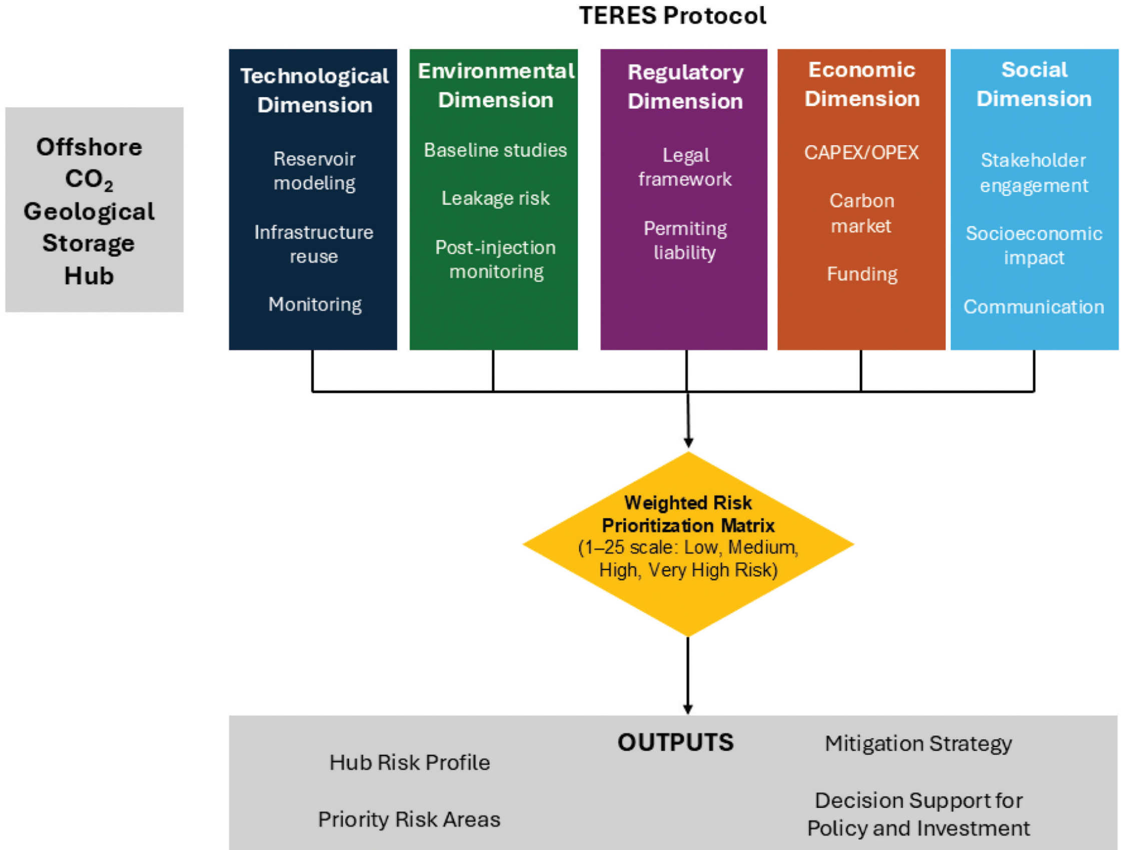

Figure 1. Structure of the TERES Protocol with its five dimensions and the weighted risk-prioritization workflow. Source: author's work. *Note*: Representative sub-indicators and the iterative feedback between technical, regulatory, and social components are discussed in Section 2.6.

2025). In contrast, the TERES Protocol is designed to be both dimensionally comprehensive and context-adaptable, enabling its application to real-case offshore environments like the Merluza Field and to broader national decarbonization strategies.

2.7. Risk weighting and scoring criteria

To operationalize the TERES Protocol's integrated assessment, a weighted risk scoring system was developed, combining expert input with ISO-based risk classification schemes. The TERES Protocol established in this study provided a structured and adaptable approach for assessing and implementing CO_2 storage hubs in offshore environments. The protocol incorporates an integrated, multidimensional framework designed to balance the various risk factors encountered in CCS projects, specifically in offshore settings such as the Merluza Field.

Weighting System Explained:

(1) Likelihood (probability of occurrence) and Impact (severity of consequence) were assessed on a scale from 1 to 5. This provided a numerical representation of risks to prioritize actions.
(2) Weight Calculation: The weighted score for each risk was calculated by multiplying the likelihood and impact, resulting in a scale that categorized risks into low, medium, high, or very high priority levels.

Scoring Scale:

1–5: Low priority—minimal oversight required.
6–10: Medium priority—monitoring is necessary.

Table 1. Scoring criteria for likelihood and impact. Source: own elaboration

Score	Likelihood Definition	Impact Definition
1	Rare: Unlikely to occur during project lifetime	Negligible: Minimal effect on operations or safety; easily reversible
2	Unlikely: Low probability based on current evidence	Minor: Limited operational impact; manageable without significant resources
3	Possible: Moderate probability under certain conditions	Moderate: Affects one or more project dimensions; requires mitigation measures
4	Likely: Known to occur in similar projects	Major: Significant disruption or cost increase; regulatory or stakeholder concern
5	Almost certain: Expected to occur without intervention	Critical: Project-threatening consequences; failure to meet safety or legal criteria

Note: Based on ISO 31,000:2018 and expert input during the development of the TERES Protocol.

11–15: High priority—requires immediate mitigation measures.
16–25: Very high priority—critical attention and urgent action required.

2.7.1. Scoring criteria and weight definition

To enhance consistency and reproducibility in the risk assessment process, the scoring system applied in the TERES Protocol was supported by structured criteria for both the likelihood and impact of identified risks. The numerical values assigned (ranging from 1 to 5) were developed based on international guidelines for risk management (e.g. ISO 31,000:2018), adapted to the CCS context, and validated through expert elicitation involving CCS specialists, geoscientists, and regulatory analysts (ISO, 2018).

The definition of likelihood scores considered the probability of occurrence based on historical data, literature, and technical diagnostics for the Merluza Field, whereas the impact scores reflected the severity of potential consequences across the technological, environmental, regulatory, economic, and social domains. Table 1 summarizes the scoring criteria adopted for both parameters.

3. Case study: Merluza field

Brazil's offshore oil and gas production is concentrated in two major sedimentary basins: the Campos Basin and the Santos Basin (Petrobras, 2020). These regions host some of the largest and most productive fields in the Southern Hemisphere. In the Santos Basin, the pre-salt cluster includes fields such as Lula, Búzios, and Iracema, characterized by ultra-deep carbonate reservoirs, high-pressure systems, and large-scale infrastructure (Petrobras). These fields are supported by extensive subsea networks, FPSOs (Floating Production Storage and Offloading units), and pipeline corridors extending to coastal terminals.

While these assets offer long-term CCS potential, their ongoing production schedules, operational complexity, and legal entanglement with multi-operator consortia may limit near-term feasibility for storage conversion. In contrast, mature fields such as Merluza, although less prominent, present realistic short-term opportunities for pilot CCS deployment, infrastructure reuse, and regulatory experimentation (Petróleo, 2020).

The choice of the Merluza Field as the case study for this research is based on a combination of geological, operational, and strategic factors. Unlike the pre-salt fields of Lula and Iracema, which are deepwater, high-pressure systems with complex carbonate reservoirs, Merluza is a mature post-salt gas field with well-documented clastic reservoirs. This significantly reduces geological uncertainty and allows for more robust modeling of CO_2 injection and containment (Petrobras, 2024; Petróleo, 2020).

In addition, Merluza has already reached an advanced stage of production decline, making it a timely candidate for potential reservoir repurposing. It also benefits from an existing offshore platform (PMLZ-1), subsea wells, and a 215 km pipeline linking it to the coastal infrastructure—all of which can be considered for reuse in a future CCS project, thereby reducing capital costs (M. R. Ciotta & Tassinari, 2020; Petrobras, 2024; Sombra, 1990).

From a research standpoint, the Merluza Field provides a realistic, data-rich setting to test the application of the TERES Protocol under regulatory and market conditions typical of early-stage CCS environments in the Global South. Its selection reflects not only geological suitability but also the practical opportunity to inform policy, investment, and governance strategies for scalable offshore carbon storage in Brazil.

The Merluza Field (Figure 2) is identified as a potential site for an offshore CO_2 storage hub due to its depleted oil and gas reservoirs and proximity to major industrial emitters. We detail the geological

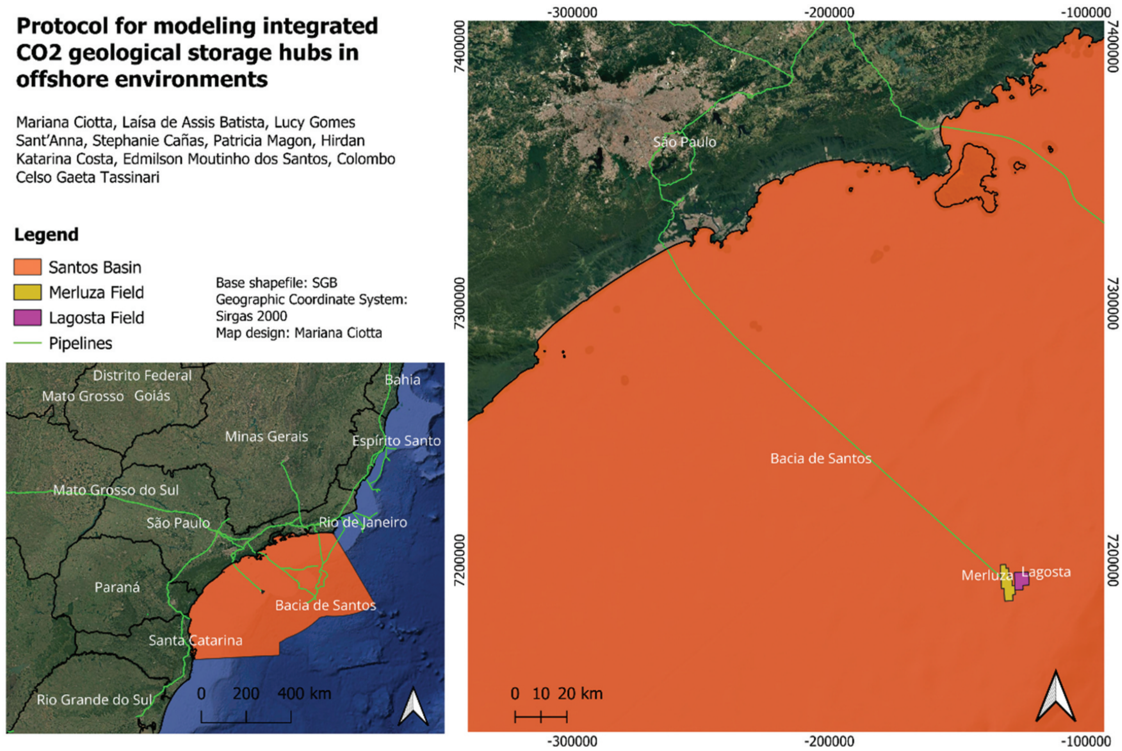

Figure 2. Merluza field location. Source: author's work.

characteristics of the field, existing infrastructure, and propose a blueprint for integration with nearby industrial activities.

3.1. General aspects and infrastructure

The selection of the Merluza Field as a case study for developing an integrated CO_2 storage protocol stems from its extensive history and infrastructure advantages. The Merluza Platform (PMLZ-1) has been operational since 1993, producing natural gas from both the Merluza and Lagosta fields (Petrobras, 2024). Geographically, it is located approximately 180 km off the coast of Praia Grande, São Paulo, positioned in a water depth of about 131 meters. This offshore location, coupled with the field's robust infrastructure, presents an ideal scenario for evaluating CO_2 storage potential (M. Ciotta et al., 2021).

The Merluza Field was the first commercial natural gas discovery under risk contracts on Brazil's continental shelf, conducted by Pecten Brazil Exploratory Company. The first drilled well (1-SPS-11) faced mechanical issues and was not fully assessed. However, the subsequent well (1-SPS-21) successfully tapped gas-saturated reservoirs at the base of the Juréia Formation. In 1984, well 1-SPS-20 confirmed gas presence in the Itajaí-Açu Formation, specifically within the Ilhabela Member, at a depth of 122 meters (Sombra, 1990).

The wells in the Merluza Field operate through natural flow and are equipped with 3½″ production columns, allowing each well to be tested individually without disrupting others. This is facilitated by the presence of both a test separator and a production separator on the Merluza Platform. Once fluids are separated (comprising gas, condensate, and water), the gas is compressed, the condensate is pumped, and the water is treated before being discarded. The combined output from the Merluza and Lagosta fields is transported to Cubatão via the PMLZ-RPBC gas pipeline, a 16″, 215 km long structure with 28.5 km onshore and the remainder offshore (Petrobras, 2024).

3.2. Geological and petrographical carachterization

The Merluza Field features two primary Santonian-age reservoirs (Upper Cretaceous, approximately 86.3 to 83.6 million years ago): the shallow marine sandstones of the Juréia Formation and the turbiditic channel sandstones of the Itajaí-Açu Formation (Ilhabela Member). The reservoirs have an average thickness of 20 to 30 meters, separated by a caprock of shale and siltstone approximately 200 meters thick. The Juréia reservoir is located at a depth of around 4,450 meters, while the Ilhabela Member is deeper, at about 4,700 meters, with temperatures reaching 150°C [40].

The Ilhabela Member showcases unusually high porosity for its depth, averaging 21% in well 1-SPS-20, while the Juréia Formation exhibits an average porosity of 12% in well 1-SPS-25. These properties contribute to favorable CO_2 injectivity and storage potential. Permeability averages 12 mD, supporting the field's capacity for safe CO_2 storage.

Petrographic and petrophysical analyses of core samples from the Ilhabela Member (wells 1-SPS-20 and 1-SPS-25) indicate hydrocarbon saturation, while the Juréia Formation (core from well 1-SPS-25) showed no hydrocarbons. The Juréia reservoir primarily comprises fine to medium sandstones with features such as small-scale cross-bedding, bioclastic layers, and clay-rich, bioturbated zones. The Ilhabela Member, on the other hand, predominantly features massive, poorly sorted sandstones with rare clay clasts and high-density turbidity current deposits (Sombra, 1990).

Petrographic studies revealed that both formations predominantly consist of quartz (~60%), feldspars (20–25%), and volcanic rock fragments (10%), classifying them as lithic arkoses. Notably, bioclasts are present in the Juréia Formation's bioclastic sandstones, comprising up to 20% of the rock volume. Volcanic fragments are mainly intermediate to acidic, with some basic rock occurrences (Sombra, 1990).

Diagenetic studies indicated differing evolutionary pathways for the two formations. The Juréia sandstones experienced significant mechanical and chemical compaction, with quartz and calcite cementation reducing porosity. In contrast, the Ilhabela Member exhibited extensive chlorite coatings around grains, contributing up to 7% of the rock volume and enhancing porosity (Sombra, 1990). The chlorite presence, identified through X-ray diffraction and scanning electron microscopy, suggests early diagenetic stages that preserved microporosity, maintaining the formation's CO_2 storage potential.

3.3. Existing data and infrastructure use

The PROMAR database provided geological, geochemical, and petrophysical information for the field, complemented by 2D and 3D seismic data. This wealth of historical data enhances reservoir modeling accuracy, aiding in the development of a tailored CO_2 storage strategy. The Merluza infrastructure, including PMLZ-1 and the PMLZ-RPBC pipeline, offers a foundation for evaluating the feasibility of retrofitting for CO_2 injection and long-term storage operations.

4. Results

The application of the Integrated Modeling and Implementation Protocol, with a focus on the Merluza Offshore Hub, yielded detailed insights into risk prioritization, project feasibility, and strategic planning across multiple dimensions. The weighted risk assessment model applied in this study highlighted the critical areas that required focused attention, ensuring the efficient allocation of resources and the alignment of project strategies with international best practices.

4.1. Detailed weighting results for the Merluza hub

4.1.1. Geological uncertainty

- Reservoir Heterogeneity: Scored as a high-priority risk (weight of 12). The variability in reservoir properties impacts CO_2 injection paths and storage efficiency, necessitating comprehensive geological characterization and 3D modeling. Advanced subsurface modeling and historical data integration were used to anticipate reservoir behavior and mitigate potential migration risks.
- Caprock Integrity: High-priority risk (weight of 10). While considered unlikely (likelihood of 2), the potential impact of CO_2 leakage due to caprock failure was critical, necessitating robust sealing integrity analyses and geomechanical studies.

- Fault Reactivation and Seismicity: Medium-priority risk (weight of 8). The risk of induced seismicity, although possible, was mitigated by the known geological stability of the Merluza Field. Geomechanical monitoring was recommended to preemptively identify any reactivation threats.
- Geochemical Interactions: Medium-priority risk (weight of 9). The interaction between CO_2 and reservoir minerals could alter porosity and permeability. Laboratory testing and long-term simulation models were used to understand the chemical reactivity and its impact on storage security.

4.1.2. Technological risks

- Well Integrity: Very high-priority risk (weight of 20). The potential for CO_2 leakage through wellbores posed a critical threat, warranting thorough well integrity checks, retrofitting, and the use of CO_2-resistant materials.
- Infrastructure Suitability: High-priority risk (weight of 12). The existing infrastructure of the Merluza platform required detailed assessments to confirm its capacity for CO_2 injection and long-term operations. Modifications were planned to enhance material compatibility and system durability.
- Monitoring and Control System Failures: Medium-priority risk (weight of 8). While the likelihood of failure was low, the impact of undetected leaks or system malfunctions could be significant. The project integrated advanced remote sensing, seismic monitoring, and pressure sensors to ensure real-time detection and control.
- Equipment Reliability: Medium-priority risk (weight of 9). The reliability of compressors, injection systems, and auxiliary technology was evaluated. Preventive maintenance schedules and equipment redundancies were implemented to mitigate downtime and operational risks.

4.1.3. Regulatory compliance risks

- Regulatory Gaps and Ambiguities: High-priority risk (weight of 12). Given the evolving nature of CCS regulations in Brazil, continuous alignment with local (ANP guidelines) and international standards (e.g. ISO CCS guidelines) was essential. Regular compliance reviews and a comprehensive permitting roadmap were developed to address any legal ambiguities.
- Permit Acquisition and Renewal: High-priority risk (weight of 12). The risk of delays in obtaining necessary permits was a key focus, underscoring the need for proactive engagement with regulatory bodies and adherence to detailed permitting timelines.
- Stakeholder and Public Acceptance: High-priority risk (weight of 12). The project required a strong public engagement strategy to foster trust and collaboration. Community consultations and transparent communication were prioritized to mitigate resistance and facilitate broader acceptance.

4.1.4. Economic viability risks

- Capital and Operational Expenditures (CAPEX and OPEX): High-priority risk (weight of 12). Financial risks related to unforeseen capital and operational costs were addressed by integrating thorough budget controls and financial forecasting.
- Carbon Market Volatility: High-priority risk (weight of 12). Given the potential fluctuations in carbon credit pricing, strategies for diversifying revenue streams and securing long-term contracts were incorporated to buffer against market instability.
- Inadequate Funding and Investment: High-priority risk (weight of 10). Although considered less likely, any occurrence could severely impact project continuity. The protocol emphasized securing multiple funding sources and government incentives.
- Long-term Liabilities and Post-Injection Monitoring Costs: High-priority risk (weight of 12). The financial burden associated with post-injection monitoring and potential remedial actions was evaluated, with sustainable funding mechanisms proposed to cover these costs.

4.1.5. Environmental risks

- Baseline Data Limitations and Ecosystem Sensitivity: High-priority risk (weight of 12). While the Merluza Field benefits from baseline environmental data derived from historical licensing activities, including marine biodiversity surveys and sediment quality assessments, these datasets are not fully tailored for post-injection monitoring of CO_2. The potential for CO_2 leakage or microseepage, though

unlikely, may have significant ecological impacts if undetected, particularly in sensitive marine habitats. The lack of standardized national protocols for offshore CO_2 environmental monitoring further elevates this risk. To address this, the project recommends adopting adaptive monitoring frameworks aligned with international best practices (e.g. OSPAR guidelines, ISO 27,914), including the integration of environmental tracers, isotopic analysis, and microbial community assessments.
- Regulatory-Environmental Interface: Medium-priority risk (weight of 9). The absence of clear regulatory guidance on environmental liability in offshore CCS projects introduces uncertainty in the definition of roles and responsibilities for long-term ecosystem protection. Coordination between environmental agencies (e.g. IBAMA), petroleum regulators (e.g. ANP), and maritime authorities is still evolving. This gap is being addressed within the scope of this project through proactive regulatory engagement and by proposing a pilot monitoring plan to inform future rule-making.

4.1.6. Social and stakeholder engagement risks

- Public Perception and Acceptance: High-priority risk (weight of 12). Despite the offshore location of the Merluza Hub, which minimizes direct impacts on coastal communities, the project's social legitimacy depends on public trust, especially regarding environmental safety and alignment with climate objectives. In Brazil, awareness of CCS remains low, and the association with oil and gas infrastructure reuse may generate skepticism. The absence of national public communication strategies on CCS amplifies these concerns. The project proposes transparent, early-stage engagement with academic institutions, civil society organizations, and environmental NGOs, along with tailored communication campaigns to demystify offshore CCS.
- Stakeholder Coordination and Governance Clarity: Medium-priority risk (weight of 10). The involvement of multiple institutional actors (including regulators, state-owned enterprises, and private partners) may lead to fragmented decision-making or blurred accountability. To mitigate this, the protocol emphasizes the creation of a stakeholder map and governance framework that defines clear communication flows, reporting structures, and shared responsibilities across institutional boundaries.

4.2. Integration and strategic implications

The TERES Protocol's comprehensive risk assessment and weighted analysis ensured a balanced approach that prioritized well integrity and infrastructure suitability while maintaining focus on regulatory compliance and economic stability. The incorporation of weighted scores allowed the project team to allocate resources effectively and develop a robust mitigation plan that preemptively addressed the most critical risks.

In addition to the isolated evaluation of each risk category, the application of the TERES Protocol revealed important interdependencies among risks that warrant integrated attention. For example, well integrity—identified as a very high-priority technological risk—has direct implications for both regulatory compliance and social acceptance. A failure in well integrity not only compromises the physical containment of CO_2, but also raises regulatory non-conformities and public perception concerns, especially in jurisdictions where CCS regulations are still maturing. This cascade effect illustrates how a single technical issue can amplify institutional and reputational risks simultaneously.

Similarly, delays or gaps in regulatory clarity may indirectly elevate economic risks by introducing uncertainty in permitting timelines, liability regimes, or eligibility for carbon credits. In turn, economic instability can erode stakeholder confidence and disrupt financing arrangements. These cross-dimensional linkages underscore the importance of adopting a systems-based risk assessment, in which risks are not treated as independent variables but as interacting components within a broader project context. The TERES framework addresses this complexity by integrating risk scoring across dimensions and enabling feedback loops between technical findings, regulatory alignment, economic forecasting, and stakeholder engagement.

4.3. Merluza hub in context: Comparison with international CCS projects

To contextualize the application of the TERES Protocol and the performance of the Merluza Offshore Hub, a benchmarking analysis was conducted comparing key parameters with selected international CCS projects. This comparison considers storage capacity, estimated cost per tonne of CO_2 stored, and project maturity, as shown in Table 2. While the values for Merluza are preliminary and based on modeling and infrastructure reuse scenarios, they indicate competitive potential when compared to active offshore storage initiatives.

Notably, Merluza's estimated storage capacity (~8–10 Mt CO_2), leveraging the depleted Ilhabela and Juréia reservoirs, aligns with small to medium-scale hubs such as Porthos (Netherlands, ~37 Mt CO_2) and Snøhvit (Norway, ~24 Mt CO_2 injected by 2023). Table 2 summarizes these parameters, suggesting that Merluza is well-positioned from a techno-economic standpoint, with lower infrastructure risk due to its known production history and reservoir performance data. However, regulatory uncertainty and the absence of an established carbon pricing mechanism in Brazil remain limiting factors in comparison to OECD countries with mature CCS governance.

When comparing the risk profile of the Merluza Hub to international CCS projects, a key difference lies in the concentration of high-priority risks. Projects such as Northern Lights (Norway) and Porthos (Netherlands) benefit from robust regulatory frameworks, public funding mechanisms, and clear liability regimes, which reduce perceived implementation risks. For example, while well integrity and infrastructure retrofitting are commonly classified as high-priority risks across all projects due to their criticality, regulatory and financial risks tend to be medium or low in jurisdictions with established CCS governance (Romasheva & Ilinova, 2019; TNO, 2019). Bennæs et al. (2024) modeled supply-chain logistics for Northern Lights, showing how large-scale offshore storage can be integrated into industrial clusters (Bennæs et al., 2024). In addition, van de Sande et al. (2024) provide an in-depth review of the governance and institutional arrangements that enabled Porthos, offering a valuable reference for contexts such as Brazil (van de Sande et al., 2024).

In the case of Merluza, the high-risk concentration stems from uncertainties in Brazil's evolving legal framework for CCS (e.g. pending approval of Bill 1425/2022), the absence of a functioning carbon market, and limited precedent in offshore licensing. These structural factors elevate risk perception across regulatory, economic, and social dimensions. As a result, the risk profile of Merluza represents a typical early-stage CCS scenario in an emerging economy, where enabling conditions are still under development.

To provide a more structured comparative assessment, we developed a qualitative proxy-weighting scheme for selected international CCS projects using the same five-dimensional structure of the TERES Protocol. Risk levels were classified as *Low*, *Medium*, or *High* based on available technical reports, public regulatory disclosures, and peer-reviewed studies.

This approach enables a more nuanced comparison of the Merluza Hub's weighted risk profile against international benchmarks. Table 3 summarizes the results.

These qualitative weightings highlight that while all projects face technological and economic uncertainties, the Merluza Hub presents a unique concentration of high risks across all dimensions. This reflects its early stage of development, emerging regulatory landscape, and the absence of consolidated public communication or carbon pricing mechanisms. In contrast, projects like Northern Lights and Snøhvit benefit from mature legal, financial, and institutional frameworks, which reduce risk exposure, particularly in the regulatory and social dimensions.

4.4. Comparative analysis of CCS protocols

Building on the benchmarking exercise presented in Section 4.4, this section expands the comparative evaluation of the TERES Protocol by analyzing how it relates to internationally recognized CCS frameworks.

Table 2. Comparative overview of the Merluza hub and international offshore CCS projects. Source: own elaboration

Project/Location	Estimated Capacity (Mt CO_2)	Storage Type	Infrastructure Reuse	Status
Merluza Hub (Brazil)	8–10 (calculated (Bachu et al., 2007)	Depleted gas field	Platform & pipeline	Feasibility stage
Porthos (Netherlands)	~37	Depleted gas field	Port + pipeline retrofit	Construction
Snøhvit (Norway)	~24 injected (to 2023)	Saline aquifer	Subsea infrastructure	Operational
Gorgon (Australia)	>100 (target)	Saline aquifer	Minimal reuse	Operational (delays)
Northern Lights (Norway)	100+ (planned phase 1–2)	Saline aquifer	New infrastructure	Under construction

Table 3. Qualitative risk levels across five dimensions. Source: own elaboration

Project/Location	Technological	Environmental	Regulatory	Economic	Social
Merluza Hub (Brazil)	High	High	High	High	High
Porthos (Netherlands)	Medium	Medium	Low	Medium	Medium
Northern Lights (Norway)	Medium	Low	Low	Medium	Low
Gorgon (Australia)	High	Medium	Medium	Medium	Low
Snøhvit (Norway)	Medium	Low	Low	Medium	Low

Note: Classifications derived from public documentation and expert analysis; "High" reflects greater implementation or acceptance challenges.

The objective is to assess how the protocol's integrated, multidimensional structure aligns with or diverges from leading practices adopted in large-scale offshore CO_2 storage initiatives.

The TERES protocol was developed through a comparative analysis of leading CCS standards worldwide, incorporating criteria from regulatory, technological, and socioeconomic domains. Benchmarking against international protocols enables an alignment with best practices while highlighting TERES's differentiated value in providing an integrated and adaptable decision-support framework.

A synthesis of reference protocols from North America, Europe, Asia, and Oceania, shown in Table 4, illustrates the variety of emphases in existing CCS guidelines. For example, the California LCFS protocol and the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) in the U.S. provide detailed requirements for site characterization, post-injection monitoring, and integrity verification over long-term timeframes, up to 100 years (NETL, 2016). These standards place strong emphasis on well integrity, post-closure liability, and accounting for emission reductions, particularly when integrating with carbon markets.

Meanwhile, protocols like GoMCarb (USA), Re-Stream (EU), and CarbonNet (Australia) reinforce the importance of infrastructure reuse, especially for offshore projects (DNV, 2021; DPI, 2014; SECARB, 2018). These frameworks include pipeline integrity criteria, proximity assessments, and economic feasibility tied to platform conversion. For instance, GoMCarb defines well requalification protocols and conditions under which infrastructure reuse may pose leakage risks or require additional remediation.

European and international regulations—such as the European Union Directive 31/EC, ISO 27,914/2017, DNV-RP-J201, and DNV-SE-0617—emphasize standardization in geological storage and CO_2 transport safety (DNV, 2019, 2022; EU, 2009; ISO, 2017). These documents often focus on new infrastructure but are increasingly being adapted to accommodate legacy systems, as evidenced by the Re-Stream Project (2021), which maps reuse opportunities across the EU for hydrogen and CCS purposes.

The comparison also shows that protocols differ in how comprehensively they address socioeconomic dimensions. While Longship (Norway) and CarbonNet include integrated public-private financing models and stakeholder engagement frameworks, others—such as Gorgon (Australia)—remain more technically oriented (CCS Norway, 2025; DPI, 2014; M H et al., 2023). Only a few, like California's LCFS, explicitly tie emission reduction accounting and permanence certification to financial instruments and regulatory incentives.

The TERES protocol incorporates and expands upon these international references by: Proposing a unified structure for technological modeling, including site characterization, pre-injection testing, and post-injection risk scenarios; Including a dedicated framework for infrastructure reuse and integrity evaluation, aligned with both U.S. (EPA Class VI, GoMCarb) and European (ISO, DNV, Re-Stream) standards; Integrating socioeconomic criteria, such as investment timing, cost-risk tradeoffs, and stakeholder acceptance metrics; Enabling adaptability to diverse regulatory regimes, including ANP and CONAMA (Brazil), OSPAR (North Sea), and international ISO norms. In this way, TERES is positioned not only as a compatible tool for international benchmarking but as a comprehensive protocol tailored for complex offshore environments, particularly where legacy oil and gas infrastructure intersects with national decarbonization strategies.

Moreover, a comparative assessment was conducted to benchmark TERES against methodologies adopted in leading CCS initiatives, including the IEAGHG Storage Site Characterisation guidelines (IEAGHG, 2009) the regulatory frameworks in the North Sea region (UK and Norway) developed by the

Table 4. Comparison between international CCS projects/protocols and the TERES protocol. Source: own elaboration

Project/protocol	Technological Assessment	Environmental Evaluation	Regulatory Alignment	Economic Feasibility	Social Dimension	Risk Prioritization	Multidimensional Integration
IEAGHG (IEAGHG, 2009)	Site characterization and injectivity modeling	Long-term monitoring and leakage pathways	General guidance, not jurisdiction-specific	Not detailed	Limited	Partial	Not fully integrated
North Sea (UK/ Norway) (2025)	Well integrity, high technical standards	Baseline and impact studies	Robust legal and permitting frameworks	Some cost analysis by operators	Stakeholder consultation required	Not formalized	Dimensions addressed separately
Porthos (Netherlands) (TNO, 2019)	Infrastructure reuse and storage modeling	Cumulative local impact studies	Aligned with EU CCS Directive	Financial modeling and subsidies	Strong public perception focus	Qualitatively addressed	Moderate integration
Gorgon (Australia) (M H et al., 2023)	Reservoir and injectivity modeling	Comprehensive environmental assessments	National regulation (Offshore Petroleum Act)	CAPEX/OPEX disclosed in reports	Limited public engagement	Implicit in documents	Technical–environmental integration
California Resources (USA) (CARB, 2025)	Capture and injection systems in existing formations	Leakage control and permanence scoring	LCFS & EPA Class VI standards	Credit-based investment mechanisms	Community and business support	Quantified via scoring	Economic–regulatory linkage
GoMCarb (USA) (SECARB, 2018)	Offshore reuse and monitoring systems	Marine ecosystem protocols	EPA Class VI and API	Public and academic co-funding	Local stakeholder collaboration	Explicit risk evaluation	Infrastructure–environment–economic framework
CarbonNet (Australia) (DPI, 2014)	Onshore/offshore modeling and innovation	Cumulative environmental assessments	National CCS regulations	Government and private co-financing	Community engagement strategies	Included in development plans	Technical–socioeconomic integration
Longship (Norway) (CCS Norway, 2025)	Full-chain CCS (capture to storage)	OSPAR-compliant marine monitoring	Norwegian legislation + OSPAR	Government and industry investment	Public-private transparency	Structured risk management	High integration across domains
Enping (China) (Zhang et al., 2024)	EOR capture and reuse	Compliance-based internal assessments	National CCS and EOR framework	State funding and tax incentives	State planning mechanisms	Partially integrated in EOR	Industry-focused integration
Ras Laffan (Qatar) (Qatargas, 2025)	Gas infrastructure conversion for CCS	Monitoring of emissions and safety	National legislation	Fully state-funded	Centralized implementation	Risk addressed via design	Policy–industry alignment
Cabiúnas (Brazil) (Petrobras)	Pilot EOR and capture integration	Licensing and environmental monitoring	ANP and CONAMA regulatory framework	Petrobras and government funding	Institutional engagement	Monitoring-based risk approach	Early-stage integration
TERES Protocol (this study)	Reservoir modeling, reuse protocols, monitoring system	Leakage risk, long-term monitoring, baseline assessments	Brazilian norms + international benchmarking	CAPEX/OPEX modeling + carbon credit sensitivity	Stakeholder mapping and communication plans	Weighted risk scoring	Fully integrated, risk-driven decision support

Note: Evaluation criteria and references summarized in Section 4.4.

North Sea Transition Authority (NSTA) and specific project protocols such as those from Porthos (Netherlands) (TNO, 2019) and Gorgon (Australia) (M H et al., 2023).

To consolidate the analysis presented above, Table 4 summarizes key international CCS protocols and projects across core evaluation dimensions. It contrasts these approaches with the integrated, risk-weighted framework of TERES, highlighting both commonalities and areas of methodological advancement.

As illustrated in Table 4, while several international protocols offer technical or regulatory components, most lack a fully integrated, risk-weighted methodology that captures the interdependencies across technological, environmental, regulatory, economic, and social domains. The TERES Protocol advances this field by offering a unified framework that not only evaluates each dimension in detail but also employs a structured prioritization mechanism to guide decision-making and risk mitigation. This adaptability makes TERES particularly suitable for emerging CCS markets such as Brazil, where infrastructure reuse, evolving regulation, and stakeholder engagement play a central role in project feasibility.

This comparative synthesis reinforces the value of TERES as a decision-support tool that is both methodologically robust and context-sensitive. By incorporating risk prioritization and integrating cross-cutting dimensions often treated in isolation, TERES bridges the gap between established international practices and the emerging needs of offshore CCS deployment in transitional regulatory environments like Brazil.

5. Discussion

The application of the Integrated Modeling and Implementation Protocol for CO_2 Storage Hubs, focused on the Merluza Field, demonstrated the effectiveness of a comprehensive framework that encompasses technological, regulatory, economic, environmental, and social aspects. This protocol provided a structured method for assessing and mitigating risks, ensuring the project's feasibility and alignment with global sustainability goals.

Detailed reservoir modeling and the assessment of existing infrastructure indicated that the Merluza Field is a promising candidate for adaptation into a CO_2 storage hub. Well integrity, identified as a very high-priority risk, required meticulous inspections and reinforcement with CO_2 -resistant materials. The study also highlighted that leveraging existing infrastructure can reduce capital costs and accelerate project timelines. This finding reinforces the strategic value of mature post-salt fields not only for technical demonstration but also for reducing the financial and logistical barriers associated with greenfield CCS projects. By focusing on asset reuse, the protocol aligns with international priorities for cost-efficient, low-risk deployment and supports a just transition for regions with legacy oil and gas infrastructure.

Environmental assessments and stakeholder consultations were crucial in ensuring minimal ecological impact and fostering transparency and community engagement. The implementation of the TERES Protocol enhanced the environmental approach by integrating robust monitoring measures to safeguard marine ecosystems and set stringent safety standards.

The study identified significant regulatory challenges, categorized as high-priority risks, necessitating continuous monitoring and alignment with both national and international guidelines. The economic analysis emphasized risks related to CAPEX and OPEX, underscoring the importance of solid financial planning and strategies to mitigate carbon credit price volatility.

The use of a weighted risk system was vital for prioritizing actions and allocating resources effectively. Well integrity and infrastructure suitability received the highest weights, directing efforts to ensure safety and project viability. This system facilitated an objective and transparent risk assessment, guiding proactive mitigation. In this sense, the TERES Protocol does not merely classify risks: it also facilitates prioritization in complex, multi-stakeholder environments where institutional, financial, and technological uncertainties overlap. The use of a transparent scoring matrix strengthens communication between technical teams, regulators, and investors, allowing for more informed project governance.

The protocol showcased strong synergy among dimensions, where technological findings informed economic projections and regulatory analyses influenced monitoring strategies. This integrated approach enabled a holistic view that balanced priorities efficiently.

5.1. Theoretical contribution

This study advances the theoretical foundations of integrated assessment for offshore CO_2 storage by formalizing TERES as a multidimensional, risk-weighted framework that treats feasibility as a problem of cross-domain governance under uncertainty. The contribution is threefold.

(i) Decision-analytic integration: TERES operationalizes a transparent, auditable structure that renders heterogeneous evidence comparable across five domains—technological, environmental, regulatory, economic, and social. By anchoring likelihood/impact judgments in standardized descriptors and aggregating them through a unified prioritization scheme, the framework strengthens early-stage decision support for complex socio-technical systems where data completeness varies and expert knowledge is essential. This advances theory beyond single-domain checklists by specifying how evidence is combined and how trade-offs are made explicit.

(ii) Interdependencies in CCS governance: the framework makes cross-domain dependency pathways explicit: technical credibility (e.g. well integrity, monitoring design) conditions regulatory confidence; regulatory clarity (e.g. permitting, liability) shapes economic bankability and risk allocation; these, in turn, influence social license and stakeholder acceptance. Demonstrating these cascades within one protocol advances theoretical understanding of CCS feasibility as an emergent property of interacting subsystems, rather than as the sum of isolated assessments.

(iii) Generalizability and benchmarking: by benchmarking the Merluza Hub against contemporary offshore initiatives and guidance, TERES clarifies the conditions under which risk profiles shift as governance matures (e.g. regulatory/economic risks attenuate as permitting and liability instruments consolidate). The framework is therefore portable: its decision kernel is general, while parameterization (indicators, weights, evidence sources) adapts to data availability, infrastructure legacy, and institutional context. This portability aligns with emerging studies of transboundary CCS networks. For instance, Nooraiepour et al. (2025) analyze the Norwegian-Polish CCS collaboration, illustrating how bilateral governance arrangements can facilitate offshore storage and reinforce the applicability of TERES in transitional regulatory environments (Nooraiepour et al., 2025). This positions TERES as a generalizable model for early-stage screening and portfolio prioritization in emerging CCS markets.

Together, these elements recast pre-feasibility as a problem of integrated risk-governance, providing a theoretically grounded and practically usable template for offshore CCS hubs. Where appropriate, we align the constructions employed here with current standards and regulatory instruments to ensure external validity and contemporaneity.

5.2. Limitations and uncertainties

Despite the comprehensive structure and integrative nature of the TERES Protocol, the implementation of offshore CO_2 storage hubs remains subject to significant uncertainties—scientific, economic, and institutional—that may affect both the performance and replicability of such projects.

From a technical and geoscientific standpoint, one of the most persistent sources of uncertainty lies in the prediction of long-term geochemical interactions between the injected CO_2 and the host reservoir rocks. Although the Merluza Field features favorable porosity and permeability, particularly in the Ilhabela Member, the long-term evolution of these properties under CO_2-rich conditions remains difficult to predict with high confidence. Reactions such as mineral dissolution, precipitation, and potential changes in wettability can alter the integrity of the reservoir and affect the ultimate storage capacity. While reactive transport models offer valuable insights, their predictive reliability is constrained by the heterogeneity of subsurface systems, the scarcity of long-term observational data, and simplifications inherent to the modeling process. These limitations underscore the need for extended laboratory experimentation and pilot-scale injection monitoring, particularly in Brazilian sedimentary basins, where CCS has not yet been implemented at commercial scale.

Economically, CCS projects are intrinsically vulnerable to fluctuations in carbon pricing and policy environments. The financial viability of the Merluza Hub—as with most CCS initiatives—depends on the stability of carbon credit markets, the availability of regulatory incentives, and the evolution of international climate agreements. In Brazil, where the carbon market is still in early development and regulatory instruments such as tax credits or carbon contracts for difference are not fully operational, project economics remain exposed to volatility. Uncertainty regarding the long-term value of carbon offsets and the absence of guaranteed revenue streams may discourage private sector participation and increase the perceived financial risk, particularly for infrastructure retrofitting projects that demand high upfront investments. The sensitivity of project feasibility to carbon pricing dynamics also calls for careful economic stress testing and the incorporation of flexible financial mechanisms that can adapt to future regulatory scenarios.

Institutionally, Brazil's regulatory landscape for CCS remains in formation. While the proposed Marco Regulatório da Captura e Armazenamento de Carbono (Bill 1425/2022) represents a significant step forward, the country still lacks a consolidated legal framework that clearly defines long-term liability, site closure obligations, ownership of injected CO_2, and monitoring responsibilities. This absence creates legal ambiguity that complicates permitting processes and hinders long-term investment planning. Moreover, offshore projects introduce additional layers of jurisdictional complexity, involving the interplay between federal environmental agencies, petroleum regulatory bodies (such as ANP), and international maritime law. The lack of precedent in licensing CO_2 storage operations in Brazilian offshore fields adds procedural uncertainty that must be anticipated and mitigated during project design.

Lastly, although the TERES Protocol integrates a social dimension, stakeholder engagement in offshore CCS projects presents unique challenges. The geographic distance from coastal communities reduces opportunities for direct interaction, which may hinder efforts to foster public trust, build informed consent, and anticipate potential opposition. Additionally, the public perception of CCS remains underdeveloped in Brazil, often conflated with continued fossil fuel dependency. These factors emphasize the need for early, transparent, and proactive communication strategies that go beyond conventional public consultation formats. Engaging with civil society, environmental NGOs, and academic institutions may be necessary to broaden the legitimacy of offshore CCS initiatives in the national climate agenda. In addition, the broader policy relevance of TERES lies in its ability to inform dynamic regulatory environments. As Brazil moves toward establishing a formal legal and fiscal framework for CCS, tools like TERES can serve as transitional instruments, bridging data gaps, standardizing project assessments, and enabling early-stage project evaluation even in the absence of comprehensive regulation.

Recognizing and critically examining these limitations is not only a matter of scientific rigor but also a prerequisite for designing robust, adaptive, and context-sensitive strategies. The effectiveness of the TERES Protocol—and its potential to serve as a reference for future CCS projects—depends on its capacity to evolve in response to these uncertainties, incorporate emerging knowledge, and align with the dynamic landscape of energy transition policies.

Beyond its technical contributions, the Merluza Hub serves as a strategic pilot case that may inform the development of national CCS governance in Brazil. The insights generated through the TERES Protocol can support the implementation of regulatory frameworks currently under legislative review, such as Bill 1425/2022, the proposed legal framework for carbon capture and storage in Brazil. As one of the first field-based assessments of offshore CCS in the country, the Merluza case offers a practical reference for decision-makers seeking to align decarbonization efforts with infrastructure reuse and geological suitability. The methodological framework and lessons learned may also be adapted for other offshore basins with similar legacy assets and emissions proximity.

6. Conclusions

The development and application of the TERES Protocol represents an original contribution to the field of carbon storage, particularly in emerging CCS contexts such as Brazil. It is the first framework to integrate technical modeling, infrastructure reuse, and risk-based prioritization using real offshore data from a Brazilian reservoir, while explicitly incorporating environmental, regulatory, economic, and social dimensions into a unified feasibility protocol.

6.1. Key conclusions

(1) Risk prioritization, focusing on well integrity and infrastructure suitability, are essential for ensuring project safety.
(2) The risk assessment with weighted scores allowed for strategic resource allocation and targeted risk mitigation.
(3) Integration of historical data and advanced modeling provided greater confidence in predicting CO_2 behavior in the reservoir.
(4) The protocol demonstrated scalability and applicability to other CCS projects in various offshore scenarios, supporting the expansion of decarbonization technologies.

6.2. Policy recommendations

Based on the findings of this study and the application of the TERES Protocol to the Merluza Field, several recommendations emerge to guide the development of public policy for CCS in Brazil:

(1) Establish a comprehensive regulatory framework for CCS that includes clear definitions for long-term liability, monitoring obligations, and property rights over stored CO_2. The ongoing legislative process surrounding Bill 1425/2022 (Marco Regulatório de CCS) should be accelerated and informed by field-based pilot experiences such as Merluza.
(2) Promote infrastructure reuse through regulatory and fiscal incentives, recognizing the value of existing offshore platforms, wells, and pipelines in reducing capital expenditure and deployment time for CCS projects. Policies could include tax credits or dedicated funding lines for retrofitting oil and gas assets for storage purposes.
(3) Develop standardized national methodologies for risk-based project evaluation, incorporating multi-dimensional assessment tools similar to the TERES Protocol. This would improve project comparability, reduce permitting ambiguity, and align Brazil's approach with international best practices.
(4) Foster public engagement and stakeholder transparency by requiring early-stage consultation for CCS projects, including offshore operations. Communication strategies should be tailored to address misconceptions about CCS and promote its role in decarbonization.
(5) Incorporate CCS into Brazil's national climate strategy and carbon pricing mechanisms, including eligibility under the regulated carbon market currently under design. Recognition of CCS as a mitigation activity would enhance investment security and support long-term project financing.

These recommendations are grounded in the technical, regulatory, and social lessons of the Merluza case and aim to support the establishment of a robust, scalable, and internationally aligned CCS policy environment in Brazil. As a field-based pilot, the Merluza Hub has the potential to catalyze the development of CCS in Brazil, both through its technical readiness and through its alignment with emerging legal instruments such as the CCS Regulatory Bill (PL 1425/2022). By providing a scalable and risk-informed assessment model, the TERES Protocol may serve not only as a project planning tool, but also as a decision-support framework for public authorities and regulatory agencies seeking to operationalize Brazil's climate commitments in offshore settings.

6.3. Future research directions

Future research may focus on extending the TERES Protocol to other geological and institutional contexts, including pre-salt reservoirs, continental onshore basins, and transboundary CCS hubs. Methodologically, there is potential to integrate the protocol with reservoir simulation platforms, economic scenario modeling, and uncertainty quantification tools to enhance predictive accuracy and decision-making support. In the Brazilian context, the protocol could also be adapted to assess CCS potential in industrial clusters or biogenic sources (e.g. BECCS), supporting the design of integrated decarbonization strategies. Additionally, comparative applications of TERES in other emerging economies would help test its flexibility and contribute to the creation of a standardized global approach to risk-informed CCS deployment. Altogether, the TERES Protocol represents a step forward in operationalizing CCS planning in emerging contexts, offering a transferable model that balances technical robustness with regulatory and social responsiveness

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Data availability statement

The datasets generated and analyzed during the current study are derived from publicly available sources, including geological, environmental, and regulatory data related to the Merluza Field in the Santos Basin. These datasets were compiled from national databases, peer-reviewed literature, and industry reports as referenced throughout the manuscript.

All relevant data supporting the findings of this study are available within the article. Additional details or clarifications can be provided by the corresponding author upon reasonable request.

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