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CCS hub for mitigation and revitalization of depleted oil and gas fields: responsible addressment of high emissions in the Brazilian coast

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Abstract:
Enabling safe and permanent storage of CO2 is crucial to the accomplishment of net zero emissions until 2050, as proposed by the Paris Agreement. By then, Brazil has committed to keep an emission ceiling of 1.2 GtCO2e, representing a drop of 50% related to values of 2005. The use of carbon capture and storage to further strengthen the fossil fuel industry brings out the ethical ambiguity of considering carbon capture, utilization and storage (CCUS) as a tool for climate mitigation. In contrast, adaption of depleted oil and gas reservoirs for CO2 storage offers a robust solution that delays decommissioning and decreases risks and costs of dealing with exhausted fields.The reuse of infrastructure also depends on the age and conditions of wells and pipelines. Here, we present carbon capture and storage (CCS) of such exhausted fields as an alternative for recovery of exploited areas, with a critical approach of this mitigation process as remediation instead of a validation tool for the current energy industry mode of production.
Keywords: Merluza; Lagosta; PROMAR; Pipeline reuse; Reservoir modeling

Garantir o armazenamento seguro e permanente de CO2 é crucial para a neutralização de emissões de carbono até 2050, conforme proposto pelo Acordo de Paris. Até lá, o Brasil se comprometeu a manter um teto de emissões de 1,2 GtCO2e, uma redução de 50% em relação ao volume emitido em 2005. O uso de captura e armazenamento de carbono para fortalecimento da indústria de combustíveis fósseis traz à tona a ambiguidade ética em considerar a captura, utilização e armazenamento de carbono (CCUS, da sigla em inglês) como ferramenta para mitigação climática. Em contrapartida, a adaptação de reservatórios depletados de óleo e gás adia o descomissionamento e pode diminuir riscos e custos da gestão de campos exauridos, embora o reúso dependa das condições e idade da infraestrutura envolvida. Aqui, apresentamos a captura e armazenamento de carbono (CCS) de campos depletados como uma alternativa para a recuperação de áreas exploradas, e abordagem crítica desse processo de mitigação como remediação em vez de ferramenta de validação para o modo de produção atual da indústria energética.
Palavras-chave:

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1. Introduction

Enabling safe and permanent storage of CO_2 is crucial to the accomplishment of net zero emissions until 2050, as proposed by the Paris Agreement (GCCSI, 2022; Poothia and Pandey 2023). By then, Brazil has committed to keep an emission ceiling of 1.2 $GtCO_2e$, representing a drop of 50% related to values of 2005 (CCS Brasil, 2022-2023). However, despite its high potential for carbon storage, there are only three initiatives currently implementing this technology in national territory: the first (2008) with utilization for enhanced oil recovery (EOR) in the pre-salt exploration of the Santos Basin (state of São Paulo); a second pilot project operating the Miranga onshore oil and gas field in the state of Bahia (2009); and a third commercial facility for mitigation of ethanol production emissions in the Mato Grosso state (GCCSI, 2022; CCS Brasil 2022-2023).

The use of carbon capture and storage to further strengthen the fossil fuel industry brings out the ethical ambiguity of considering carbon capture, utilization and storage (CCUS) as a tool for climate mitigation (e.g., Fontenelle et al., 2023). Here, we present carbon capture and storage (CCS) using exhausted oil and gas fields as an alternative for recovery of exploited areas, with a critical approach of this mitigation process as remediation instead of a validation tool for the current energy industry mode of production.

The present work discusses a feasibility protocol for implementation of CCS hubs in the Brazilian offshore basins, based on integrated modelling of technological, regulatory, and socioeconomic aspects. The CCS hub approach consists of multiple CO_2 emitters and/or multiple storage locations using shared transportation infrastructure (GCCSI, 2017; The CCUS Hub - OGCI, 2023). We use this concept to dialogue with the problem of high CO_2 emissions in the Brazilian southeast coast, in the Santos Basin region, and with the goals of the Program for Revitalization and Stimulus of Production in Offshore Fields (PROMAR). PROMAR provides an open dataset of wells and seismic data from mature offshore oil and gas fields in the Brazilian coast, to improve its production, lifetime, recovery factor, government participation, and economical performance. In this context, adaption of depleted oil and gas reservoirs for CO_2 storage is a robust solution that delays decommissioning and decreases risks and costs of dealing with exhausted fields. The modelling of the Merluza and Lagosta natural gas fields, in the Santos Basin, is presented for validation of the proposed protocol.

2. CCS hubs in depleted oil and gas field

The reuse of depleted oil and gas reservoirs is an alternative to the field decommissioning and represents a potential tool for mitigation of the emissions of CO_2 and other substances, like natural gas (Banet, 2020). The first project of this type took place in the Norway Continental Shelf: the Project Sleipner, in 1996.

Data availability from previous research and production is one of the advantages on the modelling of depleted oil and gas fields, and offshore environments are less susceptible to the public rejection (Banet, 2020). The reuse of infrastructure depends on the age and conditions of wells and pipelines, which adaption feasibility requires integrity protocols and a thorough evaluation of risks (e.g., Sachde et al., 2022; Pawar et al., 2021).

Considering the existence of hibernating depleted oil and gas fields with a platform connected via pipelines to an industrial complex in the continent (i.e., the Merluza Pole), the region of the Santos basin may benefit from adaption of these reservoirs and its infrastructure as a CCS hub for CO_2 permanent storage. Therefore, a decision-make protocol is crucial to define the feasibility of a pilot project in the study area.

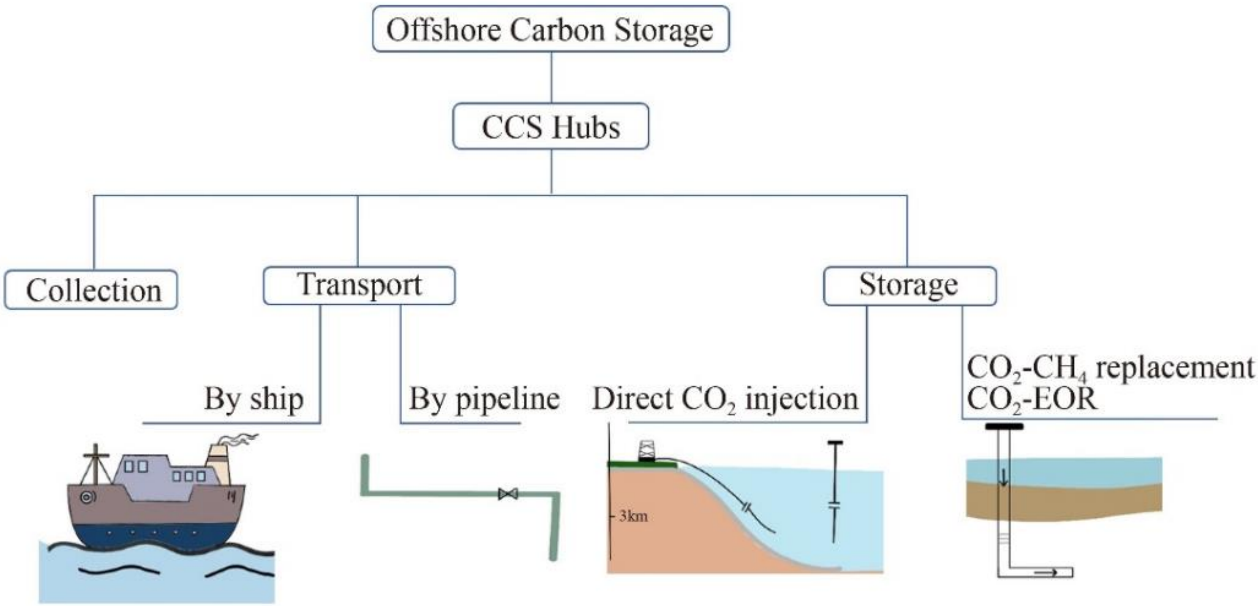

Figure 1 - General scheme for an offshore CCS. Extracted from Ku et al., 2023.

2.1. Feasibility protocol

The GCCSI Report (2022) lists about 20 CCS offshore facilities worldwide (ca. of 10% from all reported initiatives), 13 of them located in the North Sea, leaded by initiatives in Norway and in the United Kingdom. In Brazil, the only large-scale integrated project (LSIP) is operational at the Santos Basin, focused on EOR in the offshore pre-salt oil and gas production. According to PETROBRAS and the GCCSI report, more than 40 $MTCO_2$ were stored between 2008 and 2022, with a target of 80 $MTCO_2$ to be injected until 2025 – the world´s largest CCUS program in volume (25% of the global injections in 2022), and a pioneer in ultra-deep waters (PETROBRAS Agency, 2023).

While applying a decarbonization strategy with CCUS for EOR and neutralization of its current production emissions, PETROBRAS envisage integrated CCUS hubs serving industrial complexes, including hard-to-abate sectors such as the cement and steel production in its future business model, in agreement with the corporation commitment to national and global efforts against GHG emissions. An intention protocol for the first pilot project for a CCS hub was signed during the COP-28

(December, 2023): the ongoing demonstration involves the Cabiúnas Unit of Processment (Macaé, RJ) and uses a saline aquifer in the Campos Basin as reservoir. The estimated storage capacity is 100,000 tCO_2/year to start operations in 2027, and a potential impact of 20 $MtCO_2$/year after 2030.

Considering the Brazilian Nationally Determined Contributions (NDCs) to GHG abatement under the Paris agreement, the CCS viability must be seen beyond the profit frontier. The conjunction of governmental, private, scientific and societal efforts was exhaustively discussed as inherent to the accomplishment of the Brazilian plans for decarbonization and energetic transition, reinforced in the COP-28. To comply with the emission ceiling proposed until 2050 demands immediate implementation of national technical directives and subsides for CCS and CCS hubs, as the adaption of existent oil and gas regulations is not sufficient when considering permanent geological storage of CO_2 in diverse onshore or offshore context, linked or not to the oil and gas industry.

In response to this gap in the Brazilian market, a legal framework is being constructed (e.g., Projeto de Lei 1425/2022: Marco Regulatório de Captura de Carbono); with proposition and public discussion of specific norms (e.g., ABNT NBR ISO 27914 and 27916) by regulatory agencies such as ANP (Brazil National Oil, Natural Gas and Biofuels Agency) and ABNT (Brazilian Association of Technical Norms); and establishment of research and development institutions to integrate CCS science, business and society (e.g., CCS Brasil). This work contributes to the construction of a national framework of directives for CCS with a feasibility protocol for permanent storage in offshore reservoirs, focusing on a sustainable approach alternative to decommissioning.

The protocol is divided into 3 main fronts (Figure 2): i) technological modelling with a) geological technical modelling for recognition of selected rocks as ideal reservoirs for CO2 retention, and b) recognition of existing infrastructures and the need to adapt them in each analyzed case; ii) normative and regulatory studies for the understanding of the regulatory context for implementation of CCS hubs in the Brazilian coastal area, including gaps and regulatory opportunities; and iii) socioeconomic analysis for characterization of possible affected populations (human and non-human) and economic issues that limit the effectiveness of offshore CCS hubs.

For comparison, we use the structure of the California Resources Airboard CCS protocol under the Low Carbon Fuel Standard of the USA (2018); and the adaptation directives for reuse of depleted oil and gas fields in the Gulf of Mexico, through the CarbonSafe and GoMCarb projects (Table 1). Despite its leadership in commercial deployment of CCS, with the highest CCS readiness index in 2023 (GCCSI), there is no offshore LSIP currently operating in the USA. On the other hand, the recent efforts on the characterization of its offshore reservoirs (e.g., Table 1), culminating in the recent drilling of the first offshore well for CCS in the Gulf of Mexico (Offshore Magazine, 2024), suggest a rapidly changing scenario. Additionally, we present other references of protocols and specifications for CCS worldwide (Table 2), that were also considered to compose the present analysis.

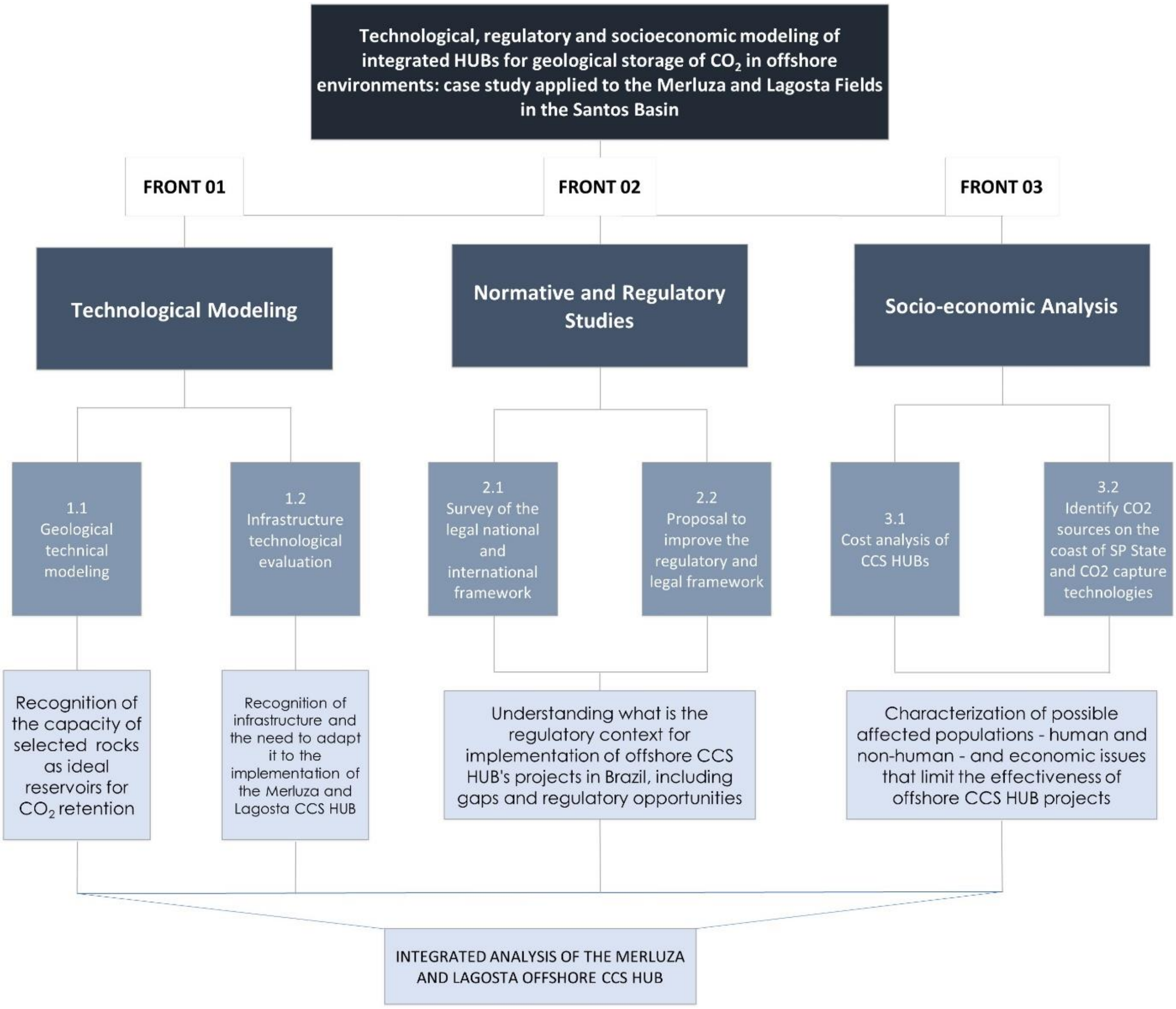

Figure 2 - Work breakdown structure of the feasibility analysis for implementation of a CCS hub in the Merluza pole, Santos Basin, southeast Brazil.

2.2. Case study: the Merluza and Lagosta fields, Santos Basin, SE-Brazil

Discovered in 1979, the Merluza field has two reservoirs: the sandstones of the Juréia Formation, deposited in a shallow platform; and the sandstones of the Itajaí-Açu Formation (Ilhabela Member), deposited in fans and channels on the neritic slope (region of the ocean with a relief of continental shelf and water column without tidal influence). These sandstones are Santonian (Upper Cretaceous, between 86.3 and 83.6 million years ago), with average porosity of 16% and permeability of 12 mD. Similar to Merluza, the Lagosta field reservoir comprises the Santonian sandstones from the Ilha-

Bela Member (Itajaí-Açu Formation), and was discovered in 2003. This reservoir presents an average porosity of 19% and permeability on the order of 4 mD (Sombra et al., 1990).

Table 1 - USA protocols for CCS and the framework adaption for reuse of depleted oil and gas reservoirs: the main topics are distributed according to the compatibility with the feasibility protocol proposed in this work.

Protocol	FRONT 1 TECHNOLOGICAL MODELING	FRONT 2 NORMATIVE AND REGULATORY STUDIES	FRONT 3 SOCIOECONOMIC ANALYSIS
Carbon Capture and Sequestration Protocol under the Low Carbon Fuel Standard (California Resources Airboard, 2018; USA)	**Site Characterization** (Minimum Site Selection Criteria + Risk assessment + Geologic and hydrologic evaluation requirements + Formation Testing and Well Logging Program + Storage Complex Delineation and Corrective Action + Computational Modeling Requirements + Storage Complex Delineation using Computational Modeling Results + Corrective Action Requirements + Plume extent evaluation + Baseline Testing and Monitoring plan) + **Well Construction and Operating Requirements** (Well Construction + Pre-Injection Testing + Injection Well Operating Requirements + Operating Restrictions and Incident Response) + **Injection monitoring requirements** (Testing and Monitoring + Mechanical Integrity Testing + Reporting of Mechanical Integrity Tests + Loss of Mechanical Integrity + CCS Project Monitoring) + **Well Plugging and Abandonment and Post-Injection Site Care and Site Closure** "For a CO2 injection well to be transitioned from a pre-existing injection, monitoring, stratigraphic test, or production well, the testing and logging **information can be provided from previous and ongoing testing and monitoring of the formation and from well tests and logs conducted during the previous use of the well."** "Any time the CCS Project Operator performs computational modeling under this subsection, **the modeling must encompass the timeframe from the beginning of the project through 100 years post-injection."**	**PERMANENCE REQUIREMENTS FOR GEOLOGIC SEQUESTRATION**: Permanence Certification of Geologic Carbon Sequestration Projects (with third part review) and Application materials + Reporting + Recordkeeping + terms and conditions **Emergency and Remedial Response+ Modification or Revocation and Reissuance of Permanence Certification** (Termination of Permanence Certifications + Minor Modification of Permanence Certifications) + **Legal Understanding, Contracts, and Post-Closure Care** **Low Carbon Fuel Standard** (title 17, California Code of Regulations, section 95480 et seq.); "MRR" the **Regulation for the Mandatory Reporting of Greenhouse Gas Emissions** (title 17, California Code of Regulations, sections 95100 et seq.); **California Code of Regulations**, section 95481; **"CA-GREET"** the Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model, as referred to in the LCFS regulation; **"CERCLA"** Comprehensive Environmental Response, Compensation, and Liability Act.; **"CAA"** Clean Air Act. **"CWA"** Clean Water Act. **"NESHAPS"** the National Emission Standards for Hazardous Pollutants preconstruction approval under the Clean Air Act; **"NPDES"** the National Pollution Discharge Elimination System under the Clean Water Act; **"PSD"** the Prevention of Significant Deterioration program under the Clean Air Act.; **Hazardous Waste Management program** - **"RCRA"** the Resource Conservation and Recovery Act.; **"SDWA"** means Safe Drinking Water Act.; **EPA Underground Injection Control Program**, 40 C.F.R. §144, §145, and §146 (2014);	**ACCOUNTING REQUIREMENTS:** (System Boundary - covers all CO2 sources, sinks, and reservoirs (SSRs) from a CCS project. All SSRs within the system boundary must be accounted for when quantifying emissions reductions from CO2 sequestration) **+ Quantification of Geologic Sequestration CO2 Emission Reductions + Invalidation and buffer account** **Financial Response**
CarbonSafe (Carbon Storage Assurance Facility Enterprise; Gulf of Mexico, 2018, USA; Meckel, Hovorka, and Trevino, 2018; Hovorka et al., 2018; Kahlor et al., 2018; Kaiser and Narra, 2018; Meckel and Trevino, 2019)	**Integration of regional stratigraphic sources:** MFS09 surface: MFS09 surface; TexLa Merge 3D; Texas OBS 3D seismic; Glenda 3D; West Cameron 3D; Vermilion 3D; 2D seismic datasets; **Seismic Amplitude Assessment**; **Assessment of Potential Storage Sites** (Structural closure: PERMEDIA software)**; Hydrocarbon-based capacity; Geometrically-based static method** (PERMEDIA software for closure analysis)**; Dynamic methods** (EASiTool software for simulation); **Integrated Risk Assessment Modeling** (IAM - based on the National Risk Assessment Program **(NRAP) Toolkit** - Geo-hydrologic Risks+Wellbore Leakage+ Monitoring Design)		**Risk and Benefit Perceptions and Information Seeking**
GoMCarb (Sachde et al., 2022; Gulf of Mexico partnership for Carbon storage; EUA)	**Pipeline Re-use Considerations** (Size/Capacity of Pipelines; Pipeline Operating Pressure; Age of Pipelines; Shore Crossings; Proximity to Source & Sink) + **Platform Re-Use Considerations** (Location/ Water Depth / Proximity to CO_2 Injection Site; Age/General Condition; Topsides Space and Weight Handling Ability vs. Requirements + **Well Re-Use Considerations** (Wellbore status; Completion date; Availability of key well integrity reports)	**Platform Re-Use Considerations** (Regulatory/Legal Considerations; e.g., transfer of liability) **DNVGL-RP-F104**: Design and operation of carbon dioxide pipelines ; **ISO 27913:2016:** Carbon dioxide capture, transportation, and geological storage — Pipeline transportation systems; **API Standard 1104**, 22nd edition: Welding Pipelines and Related Facilities (22nd edition updated to include CO2 specific guidance); **Re-Stream Report** (Europe)	**Pipeline Re-use Considerations** . (Condition/Risk of Re-use; Proximity to Source & Sink) + **Well Re-Use Considerations (**Risk for leakage or opportunity for re-use?)

The Merluza and Lagosta fields present accumulations of non-associated retrograde gas with fluid expansion as the main production mechanism. In the Merluza field, the in place condensed volume is estimated in 40.38 million of cubic meters, and 12,544.68 million of cubic meters for non-associated gas (ANP, 2016). This field accumulated a production of 14.34 million of cubic meters of oil, and

7,716.14 million of cubic meters of associated gas until the end of 2015. To the Lagosta field, the estimated in place condensed volume is 9,12 million of cubic meters, with 4,357.14 million of cubic meters of non-associated gas. By the end of 2015, its condensed accumulated production was 3,14 million of cubic meters; and 1,850,25 million of cubic meters (ANP, 2016).

Table 2 – Examples of normative and regulatory references in CC(U)S worldwide.

Region	References on CC(U)S protocols
Australia	**Australia Offshore Petroleum and GHG Storage Act**
Brazil	**PROJETO ABNT NBR ISO 27916** **PROJETO ABNT NBR ISO 27914** **Projeto de Lei 1425/2022** (Marco Regulatório de Captura de Carbono)
Canada	**Canadian Standard CSA-Z741/Alberta's RFA**
Europe	**United Kingdom Energy Act** **European Union Directive 31/EC** **Re-Stream Report -** Study on the reuse of oil and gas infrastructure for hydrogen and CCS in Europe (2021)
International	**ISO 27916**/2019 (Carbon dioxide storage using enhanced oil recovery (CO_2-EOR)) **ISO 27914**/2017 (Carbon dioxide capture, transportation and geological storage - Geological storage) **DNV-RP-J201** (Qualification for carbon dioxide capture technology) **DNV-SE-0617** (Qualification management for geological storage of CO_2)

The Merluza production platform (named PMLZ-1) was operational for 27 years, between 1993 and 2020, producing natural gas from both the Merluza and Lagosta fields. Geographically, it is located about 180 km off the coast of Praia Grande City (São Paulo state), being a fixed platform in a water depth of about 131 m (Figure 3; PETROBRAS, 2019).

The production of the Merluza and Lagosta gas fields was transported from the platform to the continent via the 215 km long PMLZ - RPBC pipeline (Figure 1). This 16″ diameter pipeline advances 28.5 km on land, connecting the platform to the Natural Gas Unit of the President Bernardes Refinery, in the city of Cubatão (ANP, 2016; PETROBRAS, 2019).

The Merluza pole kept a production of 3,6 thousand equivalent oil barrels per day until 2019. In 2020, in the pandemic context, because of the abrupt reduction on the natural gas demand (i.e., retraction between 9 and 25% compared to 2019 levels), the pole entered in hibernation and binding phase for disinvestment.

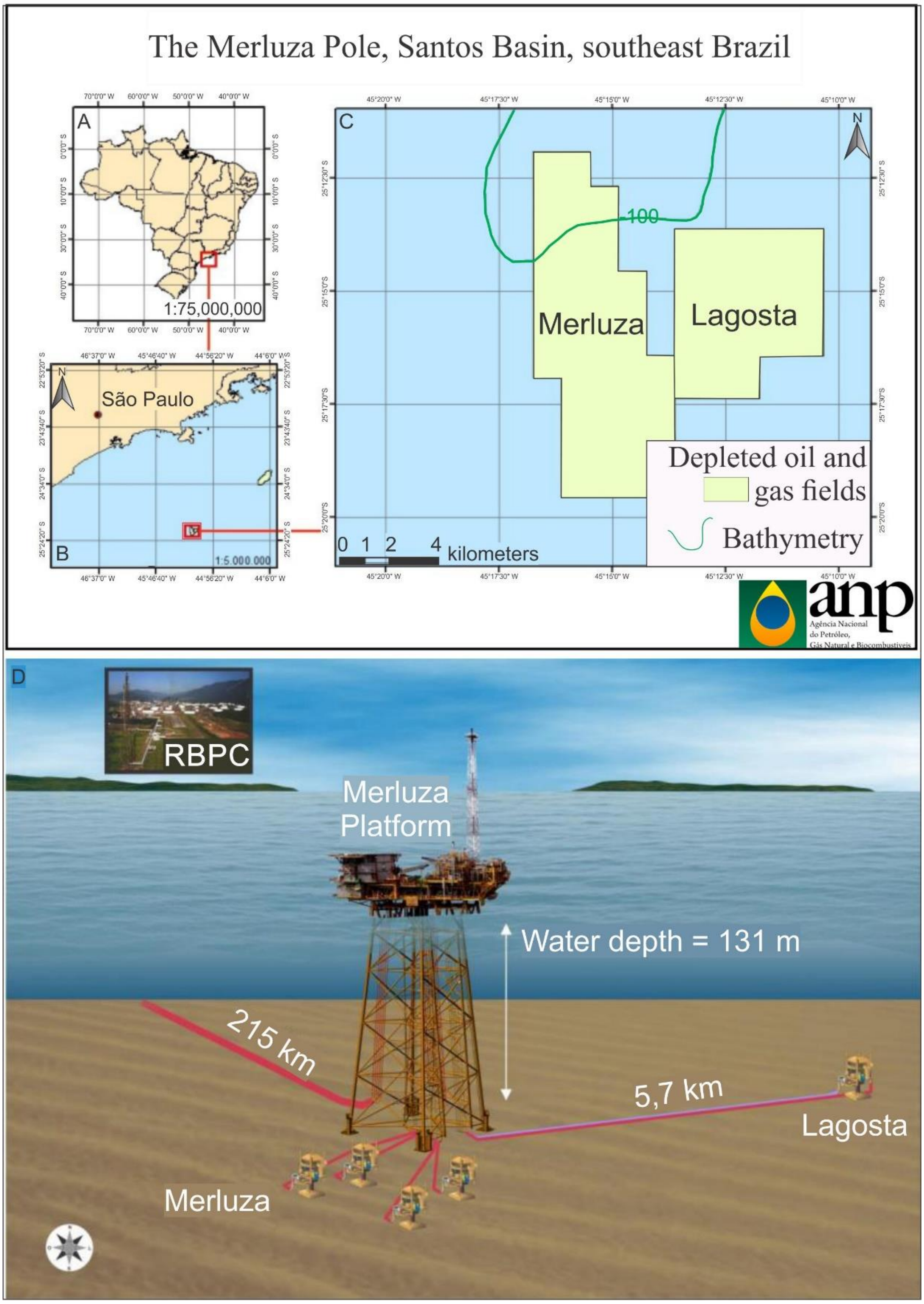

Figure 3 – A) Location of the Merluza Pole in the Brazilian offshore. B) Location of the Merluza Pole relative to the coast of the São Paulo state. C) Location of the Merluza and Lagosta fields. D) Scheme showing the Merluza Platform with indications of the natural gas fields of Merluza, Lagosta, and the pipeline responsible for transporting their production. Extracted from PETROBRAS (2019).

2.3. Preliminary conclusions

The PROMAR database provided geological, geochemical and petrophysical information on nine wells of the Merluza field, and one well from the Lagosta field, besides 2D and 3D seismic survey covering both fields (Figure 4). Production data suggest a volume capacity of about 50 Mt of CO_2 in the Merluza reservoir (Ciotta et al., 2021), and up to 157 Mt in the Santos Basin as a whole (Rocket et al., 2013). Our study is refining these numbers through further delimitation of the local storage systems and its components, protocols for integrity evaluation, and consideration of involved costs and risks for implementation.

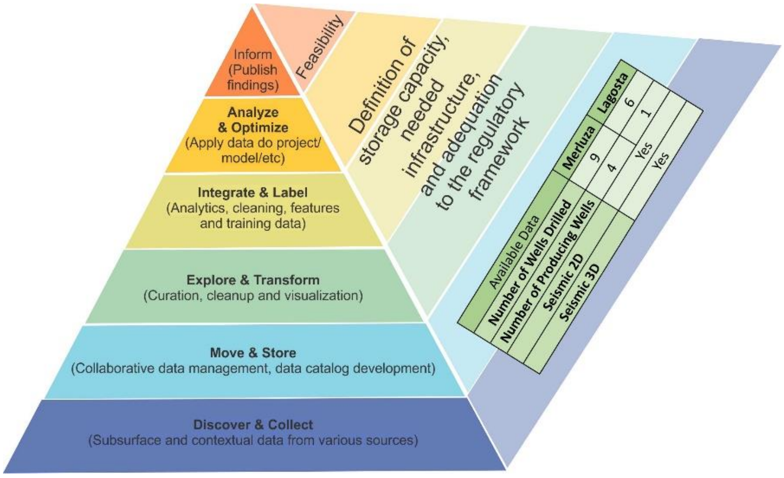

Figure 4 - Data pyramid (Morkner et al., 2021 and Yao et al., 2023) applied for analysis of the Merluza and Lagosta datasets.

Cost analysis shows that the CCS hub viability depends on the capital and operational expenditures (CapEx and OpEx, respectively), and incorporates multiple financing models (e.g., public, private, hybrid) to detail costs, risks and benefits. The most promising target source is the nearby Cubatão industrial zone, with the RPBC refinery (Refinaria Presidente Bernardes de Cubatão) standing out by its technological readiness for capture and temporary storage.

3. Concluding remarks

Depleted oil and gas reservoirs are targets with high potential for carbon storage, once those characteristics that made them good for hydrocarbon accumulation, maturation and preservation are also essential for retention of captured CO_2. As a member of the United Nations, enabling adaptation of exhausted HC-fields for mitigation of high-level emissions in current stationary industrial sources is a logical path for coupling sustainability and development in Brazil, in agreement with the national commitment to the Goals for Sustainable Development. Therefore, this work represents the vanguard approach of the Research Center for CO_2 and H_2 Geological Storage towards the development of climate crisis mitigation tools, policies, and technologies in favor of national development under a geoethical perspective.

The application of multiple techniques for geological modelling allied with specific coding programs for decision-making in risk and socioeconomic evaluation will provide the framework for the CCS hub feasibility using the Merluza and Lagosta fields for validation, also creating the adaption directives for application in other target reservoirs. This integrated modelling will enable a feasible approach for guidance of business investments, representing a bold opportunity to the oil and gas energy industry and beyond.

4. Acknowledgements

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