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A Framework Approach for Risk Assessment and Management of CO_2 Geological Storage

Talita Pontes[1*], Drielli Peyerl[2], Evandro Moretto[3]

[1,2]Institute of Energy and Environment, University of São Paulo, Brazil
[3] School of Arts, Sciences and Humanities and Institute of Energy and Environment, University of Sao Paulo, Brazil
*Corresponding author

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Abstract*—The aim of this article is to analyze the particular contributions provided by the Risk Assessment and Management framework to the CO_2 geological storage process on the offshore oil and gas sector. The CO_2 geological storage, inherent to Carbon Capture and Storage (CCS) activities, is characterized as an effective mitigation option to reduce the levels of this gas in the environment. The risk assessment allows the identification of the most significant risks and impacts, respecting the facilities characteristics, the geological conditions of the basin and the associated natural processes, assisting to propose measures that reduce the probability or the magnitude of their occurrence. Then, this analysis requires an understanding of the stages of the frameworks for Risk Assessment of CO_2 storage streams in geological formations of the main international organizations, based on studies of the literature reviewed for these purposes. In fact, the risk management procedures are necessary to maximize the intended isolation and to minimize the effects of possible CO_2 leakage. Finally, the results demonstrate a consistent relationship between the Risk Assessment and Management tool and its frameworks specificities for this activity.*

I. INTRODUCTION

Emerging Carbon Capture and Storage (CCS) technologies are primarily aimed at achieving an environmental benefit by removing large amounts of CO_2 from the atmosphere and contributing to the reduction of problems associated with climate change (Bui et al., 2018; EA, 2011). The CO_2 geological storage, inherent to this technology, is used worldwide with the potential for further expansion, as it can be considered a transition technology for reducing greenhouse gas emissions (Singh et al., 2011, 2012). Because it is an innovative method and due to the operational complexities of the project, potential risks to health, safety and the environment can occur (Abu-Khader, 2005) (Koornneef et al., 2011). In this way, understanding the risks associated with this technology becomes of fundamental importance (J. Blackford et al., 2009).

The international literature is largely focused on work associated with the International Energy Agency Greenhouse Gas R&D (Research & Development) Programme (IEA GHG) (IEA GHG, 2007; Yanagi et al., 2019). The IEA GHG has established a Risk Assessment Network from which much of the available literature has been produced (Beck & Aiken, 2009). A large portion of the work completed to date has been in the commercial sector, which inhibits the availability of detail and means that often what is available has not been peer reviewed. Much of the work under the heading of risk assessment focuses on understanding specific aspects of the sequestration and storage process that may produce a perceived risk (i.e., ultimately reducing the risk) and not on the actual risk assessment procedure itself (M. Gerstenberger et al., 2009; M. C. Gerstenberger et al., 2013).

Regarding risk assessment, it consists of several elements such as leakage probability, assessing the strength of potential environmental impact (Jerry Blackford et al., 2020), and quantifying the potential ecological, economic (Deng et al., 2017), and social impacts (J. Blackford et al., 2009). Its purpose is to identify risks scenarios and their respective consequences (Tanaka et al., 2013), assessing the potential effects on the environment and proposing measures to reduce them (OSPAR, 2007). Therefore, for an appropriate understanding of the CO_2 geological storage risk assessment, it is also important to know the regulations of the leading organizations relevant to this activity, such as European Union, Canadian Standards Association, World Resources Institute and Ministry of Environmental Protection of China, and the details of its framework (Larkin et al., 2019; Qi Li & Liu, 2015).

Thus, this study also seeks to assist the specific Risk Assessment and Management framework for CO_2 storage activities, based on experiences of risk assessment studies practiced in countries with tradition in these activities. Besides, there have been quite significant developments in research into potential environmental effects of leakage from CO_2 storage since the IPCC report in 2005 (J. Blackford et al., 2009; Jones et al., 2015; Kim et al., 2016; Paulley et al., 2013). In addition, a discussion related to the Risk Assessment and the potential risks of CO_2 storage in a geological reservoir also becomes relevant. Finally, the application of this information and approaches can assist in the Framework for Risk Assessment and Management for CO_2 geological storage activities of the offshore oil and gas sector, during the implantation and operation process of storage systems and its final abandonment.

II. METHODOLOGY

The scope of this research is associated to the risk assessment and management of CO_2 geological storage focusing on experiences correlated to the offshore oil and gas industry.

The method used is a bibliographic research of scientific articles and the main international reports (technical reports and guidance documents) recognized as reference on CO_2 storage were carried out, within the scope of CCS technology. To ensure identification of all relevant literature, relevant studies (articles and reports) encountered when reviewing other studies were also included. This research is based in a qualitative study and the following documents provide a range of data on CO_2 storage risk assessment and management submitted to interpretative analysis.

The basic references, standards and recommendations of countries with tradition in these activities, applicable to the risk assessment of offshore installations were used, considering the life cycle of a project (planning, implementation, operation and decommissioning). In addition, the existing legal, technical and scientific requirements were considered, in order to add environmental safety to the activities, as well as contribute to the identification of potential environmental impacts.

III. RISK ASSESSMENT OF CO_2 GEOLOGICAL STORAGE

A definition of risk assessment in the context of CCS was defined as the means of identifying, estimating or calculating and evaluating potential risks of storage to human health and safety, the environment and assets (Beck & Aiken, 2009). Risk assessment, which is ‘problem orientated’, was identified as part of a larger risk management framework, which focuses more on monitoring and remediation and is ‘solution orientated’. The consensus was reached that for risk assessment and communication of results, emphasis should be placed on ‘solutions’ ahead of ‘problems’ (Beck & Aiken, 2009).

Furthermore, as the CO_2 risk assessment community is still relatively new, there currently is no consensus on the appropriate methodologies for risk. Largely, the focus of the community has been guided by the lack of understanding of the reservoir behavior and the effect on the risk assessment that this implies (Ashworth et al., 2015; L’Orange Seigo et al., 2014). This makes it difficult to constrain the risks involved and makes developing a holistic probabilistic risk assessment methodology a challenge; for some events, even defining a probability of occurrence may be beyond current ability without the input of new knowledge (M. Gerstenberger et al., 2009; M. C. Gerstenberger et al., 2013).

Also, there is still no standard for risk assessment tools for this technology (M. Gerstenberger et al., 2009; M. C. Gerstenberger et al., 2013), despite the fact that new methods and tools have been developed for quantitative and qualitative risk assessment (R. Pawar et al., 2013, 2014). For example, there are researches on development of a risk assessment tool for geological storage that covers geological strata, marine environments, ground surface, ambient air and injection site and its vicinity (Tanaka et al., 2013). These methods have been integrated effectively with monitoring and mitigation techniques and deployed in the field for small-scale field tests as well as large-scale commercial projects (R. Pawar et al., 2013, 2014). Thereby, existing projects use a variety of tools, from the simplest to the sophisticated and probabilistic ones. As a single assessment standard should not be standardized in all cases, an organized set of risk assessment possibilities and tools is recommended to lead to the best possible risk estimate (M. Gerstenberger et al., 2009; M. C. Gerstenberger et al., 2013).

The potential risks of CO_2 storage in a geological reservoir can be divided into five categories, according to their main causative actions: CO_2 leakage, CH_4 leakage, seismicity, ground movement, and disposal of brine (Qi Li & Liu, 2015). The typical failure scenarios for CO_2 storage activities are leakage along a well, wellhead failure or wellbores (abandoned and in use); caprock failure, fracture or permeability; leakage with along a spill point and leakage through existing or induced faults and fractures (Chae & Lee, 2015; Koornneef et al., 2011, 2012). Clearly, the hot spot of risk research is CO_2 leakage; because there is a need to guarantee, to the extent possible, that the injected CO_2 stays safely underground (Qi Li & Liu, 2015). The analysis of CO_2 injection and potential leakage scenarios is usually associated with large underground reservoirs (Chae & Lee, 2015; Koornneef et al., 2011)

According to the European Union (EC, 2008, 2011), the storage phase has similar risks to chemical and power generation industries and was considered in Council Directive 96/61/EC. In this case, several authors discuss Risk Assessment criteria (M. C. Gerstenberger et al., 2013; He et al., 2011; Larkin et al., 2019; Qi Li & Liu, 2015; Widdicombe et al., 2013), especially related to CO2 leakages highlight to the role that risk assessments play in addressing uncertainties, which requires consideration of economic, technical, political, and social dimensions of CCS projects.

IV. FRAMEWORK FOR RISK ASSESSMENT AND MANAGEMENT OF CO_2 STORAGE STREAMS IN GEOLOGICAL FORMATIONS (FRAM)

In fact, a risk assessment can assist the process of identifying the main risks of CO_2 geological storage (Q. Li et al., 2017; Qi Li & Liu, 2015) for later identification of the potential environmental impacts inherent to this activity. Understanding its framework is significant for this purpose. The IEA GHG R&D Programme (IEA GHG, 2007) developed a risk assessment workflow diagram for the deployment of a commercial-scale storage program (Qi Li & Liu, 2015; R. Pawar et al., 2013, 2014). Previously, a Framework for Risk Assessment and Management of CO_2 storage streams in geological formations (FRAM) has been developed (OSPAR, 2007). This framework makes use of relevant developments within the framework of the London Convention/London Protocol, including developments relating to the draft Risk Assessment and Management Framework for CO_2 Sequestration in Sub-Seabed Geological Formations and developments relating to a specific London Protocol waste assessment guideline.

The risk assessment associated with CO_2 geological storage often proceed based on the ISO Standards (Q. Li et al., 2017; Qi Li & Liu, 2015) or a “self developed” workflow, according to main organizations relevant to this activity, as can be seen summarized in Table 1, that describes the risk assessment stages. According to ISO 2009:31000, risk assessment is an integral part of risk management, and it is the overall process of risk identification, risk analysis, and risk evaluation. The organizations listed, succinctly, do not have a standardized framework with each other. However, they have the hazard and/or risk identification/characterization scenarios in common in their framework, which can assist in the application of Environmental Risk Assessments for CO_2 geological storage projects.

Table.1: Stages of a framework for Risk Assessment of CO_2 storage streams in geological formations for the main international organizations.

Risk Assessment Stages	Description	Organizations’ CO_2 Storage studies
1. Context and Problem Formulation	Critical scoping step defining the boundaries of the assessment, including the scenarios and pathways to be considered	(IEA GHG 2007; OSPAR 2007)
2. Risk Source Assessment	Site selection and characterization (collection and evaluations of data concerning the site)	(EC, 2008, 2011; IEA GHG, 2007; OSPAR, 2007)
	Risk identification	(CSA Group, 2012; EC, 2008, 2011; IEA GHG, 2007; ISO ABNT, 2009; Qi Li & Liu, 2015; MEP China, 2015)

Risk Assessment Stages	Description	Organizations' CO_2 Storage studies
	Vulnerability assessment	(IEA GHG, 2007; OSPAR, 2007)
	Hazard identification: focus on the main potential pathways for CO_2 leakage	(Forbes et al., 2008)
3. Exposure Assessment	Detailed site characterization; simulation of storage complex and movement of the CO_2 stream; security, sensitivity and hazard characterization	(EC, 2011; IEA GHG, 2007; OSPAR, 2007)
4. Effect Assessment	Response of receptors within the (marine) environment resulting from potential exposure to the CO_2 stream if leakage of injected or displaced fluids were to occur.	(EC, 2011; Forbes et al., 2008; IEA GHG, 2007; OSPAR, 2007)
5. Risk Characterization	Integrates the exposure and effects data (3 e 4) to provide an estimate of the likelihood of adverse impacts (qualitative/semi-quantitative/quantitative)	(IEA GHG, 2007; OSPAR, 2007)
	Risk analysis: including risk estimation, process designed to determine the nature and level of risk, providing the basis for risk evaluation and decisions about risk treatment	(ISO ABNT, 2009; Qi Li & Liu, 2015; MEP China, 2015)
6. Risk Management	Design preventive measures based on prediction (derived from the risk assessment process). Englobes: Risk evaluation: process of comparing risk analysis results with criteria to determine whether the risk and its magnitude are acceptable or tolerable	(EC, 2008, 2011; Forbes et al., 2008; IEA GHG, 2007; ISO ABNT, 2009; Qi Li & Liu, 2015; MEP China, 2015; OSPAR, 2007)
	Risk treatment	(IEA GHG, 2007; OSPAR, 2007)
	Monitoring and verification	(EC, 2008, 2011; Forbes et al., 2008; IEA GHG, 2007; OSPAR, 2007)
	Mitigation and remediation planning	(Forbes et al., 2008; OSPAR, 2007)
7. Communication and Consultation	Defined at this article as a seventh stage, once it is a fundamental process that should permeates all stages	(Forbes et al., 2008; IEA GHG, 2007; OSPAR, 2007)

The life cycle of a CO_2 storage project consists of the following phases: planning; construction; operation; site-closure; and post-closure (Flemström et al., 2004; Manuilova et al., 2009; OSPAR, 2007). The planning, including design, construction and operation should lead to an inherently safe storage site. Each phase of the project requires all, or a selection of, the stages of the FRAM to be implemented.

The risk characterization for the storage of CO_2 streams in geological formations should be based on site-specific considerations of the potential exposure pathways, the probabilities of leakage, and potential effects on the marine environment, human health, and other legitimate uses of the maritime area (OSPAR, 2007). Thorough, a site characterization is therefore critical for defining the nature, temporal and spatial scales of potential impacts. Risk assessment plays an important role in all stages of site characterization and selection from the initial pre-screening to permitting and implementation (Beck & Aiken, 2009).

The framework of (OSPAR, 2007), similar to the (IEA GHG, 2007), describes an iterative process that should be used for continual improvement of the management of the project during the project lifecycle and improving the assessment and management of other similar projects. A simple conservative deterministic assessment is sufficient if the adverse consequences are insignificant, but if they are likely not to be, then, for precaution, the assessment should include probabilistic approaches to achieve acceptable results (OSPAR, 2007).

V. CONCLUSION

Considering the regulatory-based risk assessment and risk management frameworks, the storage site selection and characterization is often identified as the most effective approach to reduce risk; and the risk assessment for human health is specified less often than environmental effects (Larkin et al., 2019). In terms of risk management, the primary mandatory requirement is limited to monitoring, with an interactive approach recommended to monitor and re-assess risk. Other considerations such as uncertainty, stakeholder communication and consultation and the goal of transparency are not elaborated in the regulatory context, while some non-regulatory guidance is focused specially on these activities (Larkin et al., 2019).

While storage of CO_2 streams in geological formations aims to isolate CO_2 from the biosphere (including the atmosphere) permanently, risk management procedures are necessary to maximize the intended isolation and to minimize the effects of possible leaks of CO_2, incidental associated substances and substances mobilized by the CO_2 stream (OSPAR, 2007). Permanent containment of CO_2 streams is the ultimate objective of risk management. It should however, demonstrate how an event of leakage would be managed in order to prevent it leading to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area (Kim et al., 2016; OSPAR, 2007; Paulley et al., 2013; R. Pawar et al., 2014). In fact, considerable progress has been made to effectively integrate communication strategies with risk management approaches to increase stakeholder confidence in the effectiveness of deployed risk management approaches to manage risks (R. J. Pawar et al., 2015).

In addition, it is relevant to discuss, in future studies, the main sensitive or indicative variables of CO_2 leakage, which can be identified through a Framework for Risk Assessment and Management to be considered in geological CO_2 storage projects. Finally, the applicability of this information can additionally assist in the environmental risk assessment for Carbon capture and Storage (CCS) activities in the offshore Oil & Gas sector, during the implementation and operation of storage systems and its final abandonment.

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