Environmental Impact Assessment of Carbon Capture and Sequestration: General overview

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Abstract

World primary energy supply is, still, strongly dependent on fossil fuels and combustion. The contribution of renewable sources of energy in the energy mix is continuously increasing, under strong technological development and wide geographical dissemination; however, energy demand in the world is increasing faster due to population growth and upgrading living conditions expectations. According to the majority of world outlook reports [1, 2], fossil fuels are expected to continue to secure the majority of the world primary energy supply. Fossil fuels combustion is responsible for large amounts of CO_2 and other greenhouse gases emissions. CO_2 capture and underground storage (CCS) technologies are considered to represent an effective mean to dramatically reduce CO_2 emissions from large stationary sources such as power plants and other strongly dependent fossil fuel industries (cement and steel manufacturers) [3]. However, as all kind of technology or even human intervention in nature, CCS processes may involve undesirable effects on the environment. Implementation of CCS projects and activities regarding storage of CO_2 quantities above 10^5 ton are regulated by the CCS Directive 2009/31/EC [4] and also by the EIA Directive 2011/92/EU [5]. The latter replaces the former EIA Directive 85/337/EEC specifically amended in 2009 to cover capture and transport of CO_2 streams for the purposes of geological storage as well as storage sites.

This paper presents a general overview of the EIA of the CCS technologies, with a particular focus over legal framework and the possible environmental impacts on CO_2 storage sites, considering two reservoirs types: abandoned or unmineable coal seams and deep saline aquifers.

Keywords: CCS; EIA; CO_2 storage; risks;

Introduction

World Energy demand and supply

Presently the model of primary energy supply is based on fossil fuels accounting of more than 80% of total primary energy consumed in the world as presented in Figure 1.

Driven by global population growth and people legitimate expectations on improving health and living conditions, the world energy demand is in constant growth, and yet, energy does not constitute a commodity accessible to everybody, especially in undeveloped countries [6]. Technologies using renewable energy have experienced a great progress in the last decades; however, energy consumption is increasing faster than growing population and especially in developed countries, *per capita* energy consumption is affected by rising dependency on electric and electronic devices. In some undeveloped countries, implementation of the latest technologies to transform energy is restricted, mainly by economic reasons, and the use and transformation of energy is achieved by traditional, low efficient and even sometimes, obsolete production methods. Conventional burning of fossil fuels is a long term known and widely disseminated use of energy and still today, consists of the cheapest way to obtaining energy providing for basic and essential needs and also for important industries for countries' economies such as cement and steel manufacturers.

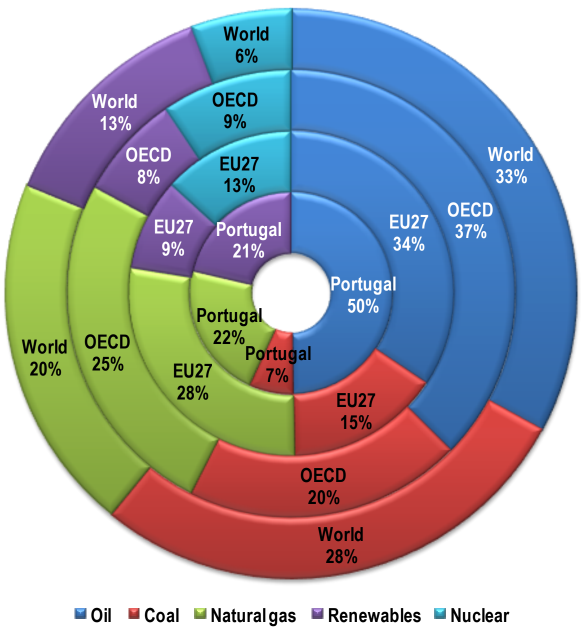

Figure 1. – ***Primary energy supply in 2010***, representing the principal primary energy sources and four levels of consumption: world, OECD, European Union and Portugal. "Renewables" includes: biomass, wind, hydropower, geothermic energy, solar energy, wave and tide energy but also waste combustion. Sources of data: for Portugal from DGEG [7] and Eurostat [8, 9]; for European Union from Eurostat [8, 9], for OECD and the world, data from IEA [1, 6], from OECD [10] and EIA/ DOE [2].

GHG concentration in atmosphere and CCS

The continuous growth of world energy consumption has been pressuring the environment, specifically in what concerns the emission of pollutants into the atmosphere, mainly substances with greenhouse effect. Carbon dioxide (CO_2) is a greenhouse gas (GHG) whose production and release is inherently associated to combustion of fossil fuels. Since the 20th century (especially the 2nd half), the emission of CO_2 from fossil fuels combustion has increased extraordinarily [11].

Carbon Capture and Storage (CCS) comprises several technologies that aim to reduce or prevent the release of CO_2 resulting from industrial processes to the atmosphere [3]. These include:

- Capturing of CO_2 from gaseous effluents: separation of CO_2 from other flue gases, compression for volume reduction and fluid accommodation;
- Transport of compressed CO_2 through pipeline, by shipment or by truck, from production unit to the storage site;
- Injection of CO_2 for underground storage (within several possibilities: depleted hydrocarbons reservoirs, abandoned or unmineable coal seams and deep saline aquifers).

At the current state of the art, CCS technologies can only capture GHG emissions from stationary sources, which nevertheless represent a considerable amount of the total CO_2 emissions.

CCS legal framework

Implementation of CCS projects and activities regarding storage of CO_2 quantities above 100 kton are regulated by the CCS Directive 2009/31/EC [4] and also by the EIA Directive 2011/92/EU [5]. The latter codified the former EIA Directive 85/337/EEC that was specifically amended in 2009 to cover capture and transport of CO_2 streams for the purposes of geological storage as well as storage sites pursuant to CCS Directive 2009/31/EC. Thus, Directive 2009/31/EC amended the Annexes I and II of the EIA Directive, by adding projects related to the transport, capture and storage of carbon dioxide (CO_2). All projects referred in this list are considered mandatory for Environmental Impact Assessment.

Table I describes the CCS project life cycle considering the obligations settled in both CCS and EIA Directives.

Table I. Life cycle of a CCS project for safe storage implementation and related activities considering the obligations settled in the CCS Directive and in the EIA Directive. Also according with [12].

<table>
<tr><th>CCS Project / activity phase</th><th>CCS Directive (2009/31/EC)</th><th>EIA Directive (2011/92/EU)</th></tr>
<tr><td rowspan="2">Phase 0
Screening criteria for site selection
Planning
Project feasibility evaluation
Local storage risks assessment
EIA Report</td><td colspan="2">Detailed project description
Complete geographic, geological and environmental characterisation of selected site and surrounding area including qualitative risks assessment
Storage complex characterization</td></tr>
<tr><td>Explorations permits request
Development of site specific monitoring, control and corrective measures plan
Application for storage permit
Requires: EIA full report submitted and approval</td><td>Environment Impact Assessment procedure</td></tr>
<tr><td>Phase 1
Construction and substructures for site testing and operation</td><td rowspan="3">Site specific Monitoring, Control and Corrective Measures Plan development
Possible environmental impacts as criteria in strategic decision making
Mitigation measures incorporated in the facility design: project review</td><td rowspan="3">Monitoring of significant effects on the environment and effectiveness of the control measures
Quantitative risks assessment: re-evaluation of EIA report</td></tr>
<tr><td>Phase 2
Testing: CO_2 Injection tests</td></tr>
<tr><td>Phase 3
Operation: CO_2 storage at commercial scale</td></tr>
<tr><td>Phase 4
Deactivation: site closure and decommissioning</td><td colspan="2">Maintenance of the specific Monitoring, Control and Corrective Measures Plan
Quantitative risks and impacts recording and evaluation</td></tr>
</table>

Pursuant to CCS Directive 2009/31/EC, a geological formation can only be selected as a storage site, following the screening criteria for safe storage of CO_2, if there is no significant risk of leakage, and no significant environmental or health risks exist. To identify and evaluate the risks associated to a potential storage site, a complete characterisation and assessment of the potential storage complex and surrounding area must be carried out, according to the best practices [13, 14] comprising: (1) Data collection to construct a 3-D static model of the reservoir, the caprock, and the surrounding area, including the hydraulically connected areas; (2) Building the 3-D static geological earth model, developing a range of scenarios for each parameter and calculating the appropriate confidence limits and the associated uncertainty; (3) Characterisation of the storage complex dynamic behaviour, the sensitivity characterisation and the risk assessment, through computerised simulations of CO_2 injection into the storage site.

Specifically, three fundamental features of a reservoir are crucial for development of the reservoir model and also to consider the reservoir as a potential storage site [15, 16]:

- Capacity - the space available in the reservoir for CO_2 storage: depends on the reservoir the dimension (volumetrics) and pore space characterisation;
- Containment - existence of several CO_2 trapping mechanisms, namely a sealing layer or cap rock (and also other low permeability layers in the overburden);
- Injectivity - the rate of CO_2 injection in the reservoir is dependent on several reservoir characteristics especially the depth, the pressure but, above all, the permeability of the rock formation.

Still according to CCS Directive, the storage complex monitoring plan has to be establishing and updating. Pursuant to CCS Directive monitoring requirements, the plan must take into account: detection of CO_2 migration; detection of CO_2 leakage; quantification of effects on the surrounding environment, including the biosphere and all its resources particularly human populations. The monitoring plan must provide details of the monitoring to be deployed at the main stages of the project, including baseline, operational and post-closure monitoring. Besides the monitoring plan, a mitigation and corrective measures plan assesses the effectiveness of any corrective measures; updating the assessment of the safety and integrity of the storage complex in the short and long term, including the assessment of whether the stored CO_2 will be completely and permanently contained [14].

Environmental impact assessment of CCS

To achieve an Environmental Impact Assessment of a CCS project, the entire life cycle of the projected unit has to be evaluated concerning, not only the environmental issues, but also the social and economic effects of the project and risk assessment. Thus, the objective of the EIA is to identify the possible origins of problems, to propose alternatives and to define measures in order to avoid, reduce and, if possible, remedy significant adverse effects.

As mentioned before, a CCS project consists of the capture of carbon dioxide (CO_2) from industrial installations, its transport to a storage site and its injection into a suitable underground geological formation for the purposes of permanent storage. The novelty of CO_2 geologic storage EIA, relatively to other industrial projects, arises, precisely, from the concept of *permanent* which means a CO_2 residence time of thousands of years in the storage complex. Considering such a perpetual underground storage, some authors tend to establish comparisons between CO_2 geological sequestration (CGS) and disposal of radioactive waste, however, besides the required permanent storage in underground rock formations; there are no other similarities between these two situations.

CO_2 geologic storage (CGS), like other type of hard technologic projects may have impacts on:

- Human Health and Safety;
- Biodiversity;
- Atmospheric Environment (including GHG emissions and noise);
- Water (groundwater and surface water);
- Geology (soils and underground space);
- Waste (including construction debris),

besides the socioeconomic impact on neighbour populations. CCS units, considering the storage phase (CGS), have specific risks, the most important are summarised in Table II.

Table II. Specific risks associated to the storage in CCS units

On-shore storage risk identification [17], [18], [19], [20], [21]	**Probability of occurrence**	**Direct and indirect consequences of the event occurrence**	**Risk level**	**Impact level**[22]
Overpressure in the reservoir due to CO_2 injection and storage [23]	***Very low*** *(controlled by mitigation measures; limitation of injectivity and CO_2 flow pressure)*	Rise of hydrostatic pressure in the reservoir: displacement of brine (saline aquifers) or other fluids (as CH_4, from coal seams) Activation of micro fractures and /or faults as a result from hydrostatic pressure elevation Temporary or definite lack of capacity of the reservoir: Impossibility of further CO_2 injection in the site - Selection of other CCS unit or inactivity (Closure of the CCS unit)	*Low* (COAL) to *Moderate* (AQUIFERS)	Irrelevant to Significant but mitigable
Migration of CO_2 into neighbour geologic formations [21]	Very high (*expected behaviour of CO_2 plume*)	Lateral and/or descendent diffusion of CO_2 from the storage complex into neighbour formations (the caprock - top sealing rock layer is, by definition, impermeable to CO_2) CO_2 Reactive processes with minerals of neighbour geologic formations (secondary trap mechanisms occurring at long-term storage)	Very Low	Irrelevant
Migration of CO_2 into neighbour aquifers or aquitards [21]	Very low *(screening criteria for site selection excludes locations near aquifers or aquitards)*	Dissolution of CO_2 into the water, possible pH decrease and water acidification; Reaction of CO_2 with other water dissolved substances; Potable water contamination with impurities (from the CO_2 stream such as H_2S)	Very High	Significant not mitigable
Leakage of CO_2 into the atmosphere from storage complex through[21], [23]: 1. Caprock 2. Injection wellbores 3. Abandoned well bores[24]	1.Unlikely *(containment criteria for site selection)*	Possibility of CO_2 entry into the caprock due to integrity failure (caused by unexpected geologic events such as an earthquake) Possibility of CO_2 to find a way through the overburden to the subsurface, ground waters or even the atmosphere	Acute	Significant not mitigable
	2. Low and 3. Low *(continuous monitoring of wells during operation and post-closure phases; mitigation and remediation plans)*	Flow of fluids along the well (CO_2 and possibly also brine) caused by: • failure of well integrity or improper sealing of an injection well • degradation of well cement , casing or plugging after long-term storage period • Eventual penetration of CO_2 leaking flow into the subsurface , ground waters or even atmosphere	Moderate to Very High (*depends on CO_2 flow rate through well*)	Significant but mitigable
Soil and ground water disruption after long-term storage	Not Yet Determined (*requires further data from tests and field experience from existing CCS units*)	Possibility of ground movement and fracture through induced micro seismicity and stress Possibility of groundwater circulation disturbance cause by fracturing activation or expansion Possibility of uplift or subsidence of layers caused by overpressure of the reservoir	Acute	Unknown (but probably not mitigable)

Risks Level: Very Low → Low → Moderate → High → Very High → Acute

Impact level: Irrelevant → Significant but mitigable → Significant but not mitigable

Discussion

The environmental impact is highly dependent on the characteristics of underground geological formation for the purposes of permanent storage of the CO_2, partly due to overpressure issues of the reservoir and lithologies adjacent to the storage reservoir. The capacity of each reservoir has to be estimated using reservoir modelling and then calculated using the experimental results of injection tests. During injection of CO_2 the real pressure inside the reservoir has to be continuously monitored to prevent localised overpressure. Control of CO_2 pressure and flow is particularly important at the injection phase, because the CO_2 injection flow (injectivity) must match the permeability of the reservoir to avoid local accumulation of fluid and eventual overpressure [23].

Coal has the ability to swell with pressure and the CO_2 injected into coal seams is chemically adsorbed, remaining adherent to the walls of the coal pores in a coalescent supercritical state [3, 16]. CO_2 stored in saline aquifers is absorbed and dissolved in the saline water, and also, eventually, part of the injected amount may have reacted with other dissolved minerals in the aquifer.

Starting at injection and mainly during storing phase, it is expected that CO_2 is circulating all over the reservoir, including other permeable lithologies adjacent to the storage reservoir, tending towards equilibrium. However, it is imperative that the lithology on the reservoir top (the caprock) must be impermeable to CO_2, though preventing CO_2 migration in ascending direction and eventual reach to the surface. If such an event occurs, resulting from natural migration pathways, such as existing boreholes, recent faults or even outcropping permeable formations, the upward CO_2 has to find its way up passing through several layers of (probably different) lithologies with also different permeabilities. An eventual leakage from underground is a slow process that may last for decades or even centuries, depending on the diffusion capacity of the CO_2 through the geologic formations above the reservoir layer, until the CO_2 finally reach the surface. The magnitude of an eventual underground leakage may be predicted by the required 3-D dynamic geological model of the reservoir formation and the neighbours' lithologies. Phase 2 of a CCS project – CO_2 injection tests must provide results to quantify the extension of a possible underground leakage. On the other hand, surface leakages, such as resulting from operator human error or equipment mal-functioning, may have an immediate impact in the health and safety of the operators and other CCS unit staff and also on the vegetation and other natural resources in the region of influence. In this case, the emergency situation, and the correspondent required plan of action for its remediation, is not very different from other types of industries. CO_2 isn't a combustive or an inflammable agent, the risks of a rising concentration result from its toxicity. Typical open air concentrations of CO_2 vary oscillate from 0.03% to 0.04%, and indoor levels may reach 0.06%, in poor ventilated spaces. Toxicity of CO_2 is, usually, considered to happen from concentrations rising from 5% and above and irreversible health effects are reported to occur at very high levels of CO_2, above 6% and for an exposure time of several (15 – 20 minutes).

Conclusions

In a near future, CCS will represent a significant way to reduce CO_2 emissions from large stationary sources and these technologies will experience dissemination and deployment all over the world. The novel use of the underground space by CGS in alliance with the wide timeframe of these projects, which aim to permanent storage, represents a new paradigm and also new technologic challenges. Within this new framework, EU environmental legislation and also some international agreements were modified to include the specificities of CGS technologies and concepts. The assessment of risks associated with CGS can only be properly estimated using trustful, real models of the potential storage complex; however, quantification of risks leading to the EIA can only be evaluated after local field testing.

Although deep saline aquifers are considerer to represent a huge potential for CO_2 storage and are geographically available all over the world, in our point of view, in countries where hydrocarbons reservoirs are nonexistent (just as the case of Portugal), abandoned or unmineable coal seams represent a better potential location for permanent storage of CO_2. The safety of CO_2 sequestration relies on geological, both chemical and physical, trapping mechanisms for CO_2, which are different for saline aquifers and for coal seams. CO_2 occurs naturally in coal seams, associated with other gases (such as methane). Coal adsorbs CO_2 preferably to other gases, while in saline aquifers the injected CO_2 will not be adsorbed and will compete for underground space with brine, most probably causing its displacement. Because of this, overpressure of the storage reservoir is most likely to occur sooner in aquifers than in coal seams.

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