Carbon Capture and Storage

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Carbon capture and storage (CCS) is a developed technology to minimize CO_2 emissions and reduce global climate change. Currently, shale gas formations are considered as a suitable target for CO_2 sequestration projects predominantly due to their wide availability. However, the injected CO_2 causes possible geochemical interactions with the shale formation during storage applications. The CO_2/shale interaction is a key factor for the efficiency of CCS in shales, as it can significantly alter the shale properties. This paper reviews the current knowledge of the CO_2/shale interactions and describes the results achieved to date, to gain an in-depth understanding of the impact of CO_2/shale interaction on shale properties. With this evolving technology, further studies are needed to include various shale formations and identify how different shales' mineralogy could affect the CO_2 storage capacity in the long-term.

shale gas | CO2 injection | CO2 sequestration | CO2 storage capacity | CO2/shale interaction

1. Introduction

The development of carbon capture and storage (CCS) stands as a suitable technology to reduce the massive increase in CO_2 emissions in recent decades, as global climate change is becoming a serious concern to the public environment and economic growth [1]. CO_2 geological sequestration was proposed as a reliable technique to mitigate the emissions of greenhouse gas from fossil fuels into the atmosphere, by injecting CO_2 for long-term storage and enhancing gas recovery [2][3][4]. The success in developing shale formations in recent decades has shifted attention towards shale reservoirs, and considered them as promising candidates to store CO_2 for extended periods [5], mainly because shales with their ultralow permeability play a major role as barriers or seals in a petroleum reservoir system, and also due to their wide availability worldwide [6][7][8][9][10][11][12]. CO_2 is a relatively reactive substance; once injected into the shale formation, it will be trapped in the adsorbed phase. In the long-term, formation brine will dissolve the injected CO_2 and causes reactions with the shale rock, leading to mineral precipitation and dissolution which may affect the shale storage capacity [1][13]. The CO_2/shale interaction is a key factor for the efficiency of CCS in shale formations; it can significantly alter the shale properties, which in return affect the rock geometry, fluid transportation, and storage capacity [14][15]. This paper focuses on reviewing the existing knowledge of CO_2/shale interactions and describing the results achieved to date. It provides a comprehensive-systematic review on the alteration of the physical, chemical, and mechanical properties of shale caused by CO_2 exposure. It also highlights the topics on Life Cycle Assessment (LCA) and the economic viability of CCS applications in shales.

2. Environmental Evaluation of CCS

The environmental consequences of CCS are often evaluated through Life Cycle Assessment (LCA) studies. LCA is proven to provide a complete analysis of all environmental effects of applying CCS to power plants. Such studies are detailed and time-consuming and vary in scope, methodology, and outcomes, but they provide a suitable assessment of many environmental effects, including global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP) and cumulative energy demand (CED) [16]. Generally, there are three main factors incorporated to influence the environmental effects from the CCS systems [17]: (1) efficiency energy penalty, (2) purity and capture efficiency of CO_2, and (3) origin and composition of the fuel. However, CO_2 capturing is out of the scope of the current study. Energy penalties are associated with the capture technology, generally, pre-combustion processes produce lower energy penalties compared to pre-combustion and oxyfuel processes [18][19]. For instance, 29.6% of post-combustion thermal efficiency for hard coal was reported by Schreiber et al. [20], while 48% of thermal efficiency was reported with the pre-combustion process [19]. This variation can be attributed to the different types of fuel composition (natural gas, coal), assumptions in time scale, and the different energy sources (gas, hard coal, bituminous, lignite) [17]. For an electricity production process, CO_2 is produced in different purities and captured by the different systems. Therefore by minimizing the consumption of electricity for the CO_2 capture, the energy penalty is reduced, and thus reduces the environmental effects from the CCS system [17]. Hard coal is considered as a valuable and wide available fuel to capture CO_2; one LCA study shows that the power generation from hard coal has significantly reduced the GWP, indicating about 13% contribution to the total GWP for post-combustion [21]. Similarly, the power generation from lignite power plant reduces the GWP, with lower share to the global total GWP compared to hard coal [22], due to the production of mono-ethanolamine during the capture process. However, natural gas implies higher efficiency in capturing process compared to hard coal and lignite, with a reported thermal efficiency of 49.6% and 44.7% in post-combustion and oxyfuel processes, respectively [20]. This results in lowering the GWP of power plants and increases the efficiency in CO_2 capture.

3. Economic Viability of CCS in Shales Shale

Shale formations hold a promising potential to utilize CCS projects in terms of their technical feasibility. By combining ESGR operations with long-term CO_2 storage applications, CH_4 production can be maximized due to the strong adsorption capacity of CO_2. However, the economic viability of CCS in shales has yet to be proven, as the related literature on this topic is limited. Considering the associated costs of CO_2 capture, transport, and storage, together with infrastructure cost and petro-physical characteristics of shales could make CCS project costly [23][24]. Mainly, there are two components of the cost of CO_2 capture. First is the cost of removing CO_2 from industrial emissions, as, currently, chemical adsorption of CO_2 is believed to be the best available technology [25]. Secondly, the cost of equipment and chemicals, as they increase the overall capture capital cost. CO_2 capture is more of a technical factor, and innovative technologies are needed to reduce the costs of CO_2 capture and deliver stable long-term benefits [26]. The costs of CO_2 injection and transportation are dominant factors affecting the economic viability of CCS in shales. These costs are controlled by the potential revenue form CH_4 production and other factors including well spacing, CO_2 separation, and bottom-hole pressure [27]. The CO_2 injection cost is related directly to the CO_2 injectivity approach used, i.e., the applied huff-n-puff processes in the Big Sinking Field showed an increase in injection cost by USD 0.35/metric tonnes [28]. Although CO_2 injection is costly, integrated CCS systems in shales estimated a reduction of 30% on the average of the CO_2 injection cost, with an average of USD 5–10/metric tonnes lower cost compared to saline aquifer [29]. However, the added cost of CO_2 transportation is large compared to injection and capture costs. A study [27] on Marcellus shales estimated a cost of USD 60–70/metric tonnes to transport CO_2 from industrial source to the site, added to the USD 22.4/metric cost of CO_2 injection. These results indicate that using shorter pipeline transport distances with smaller diameters could be a suitable method to reduce the transport cost, which eventually implies high incremental capital costs.

Apart from the consideration of the fixed costs, the application of CCS is derived by other factors, mainly related to the concerns regarding carbon price and carbon tax revenues [30]. Addressing this topic is within the gaps between the economic theory and reality that prevents CCS to have an international breakthrough [31]. Another concern about integrated CCS systems is how they can be utilized for large-scale fossil fuel power plants instead of refining industries only. However, reviewing and discussing these factors is out of the scope of this paper, yet it is reliable for generally highlighting these economic drivers and their impact on CCS deployment (Table 1). In summary, more studies are needed to provide clear assessments of the economic viability of CCS in shales. Although the application of CCS in shales is encouraging, the lack of available knowledge regarding storage capacity, reservoir data for best sequestration settings, and the effect of long-term CO_2/shale interaction can affect its economic viability.

Table 1. Economic drivers for CCS projects [31]

Environmental Policy	Cost of CCS	Fossil Fuel Energy Costs	Clean Energy Sources
This is the main driver for CCS technology, as it controls the economic market and energy generation. The demand for CCS will depend on the employed strategy that targets carbon emissions through “carbon tax” revenues.	For the CCS project to be cost-effective, the unit cost to capture, transport and storage has to be lower than the emitting CO_2 and pay the carbon price. A more advanced CCS technology will lead to an increase in energy generation from fossil	Fossil fuel resources are limited in nature, and the increase of generating fossil fuel energy costs will affect the level of fossil fuel energy, carbon emissions, and overall CCS activity. Therefore, due to the exhaustibility and	There is an approach to utilize carbon-free resources i.e., solar energy, wind and nuclear electric power to replace or at least contribute to energy generated from fossil fuels. It will be ideal to employ clean energy sources only, as generating energy cost is low, which puts CCS in

When carbon emissions are optimally taxed, this allows for the non-energy cost of CCS to drop, and thus lowers the emissions tax [30]. In this case, a lower carbon tax provides the opportunity for companies to apply CCS projects.	fuels and reduce the unit cost of CCS. Moreover, the availability of geological sequestration sites will also result in a higher level of CCS.	scarcity rent cost, renewable resources should be considered as a possible alternative for fossil fuels, which may help to achieve a higher level of CCS [32].	high demand, but the full replacement of fossil fuels is not expected soon. As of today, 80% of the global energy needs are supplied by fossil fuels, however, by combining both sources with optimal timing, the cost of energy generation can be reduced, and thus increases the level of CCS [33].

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