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Active and integrated management of water resources throughout CO_2 capture and sequestration operations

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Abstract

Most projected climate change mitigation strategies will require a significant expansion of CO_2 Capture and Sequestration (CCS) in the next two decades. Four major categories of challenges are being actively researched: CO_2 capture cost, geological sequestration safety, legal and regulatory barriers, and public acceptance. Herein we propose an additional major challenge category across all CCS operations: water management. For example a coal-fired power plant retrofitted for CCS requires twice as much cooling water as the original plant. This increased demand may be accommodated by brine extraction and treatment, which would concurrently function as large-scale pressure management and a potential source of freshwater. At present the interactions among freshwater extraction, CO_2 injection, and brine management are being considered too narrowly -in the case of freshwater almost completely overlooked- in the technical and regulatory CCS community. This paper presents an overview of each of these challenges and potential integration opportunities. Active management of CCS operations through an integrated approach -including brine production, treatment, use for cooling, and partial reinjection- can address challenges simultaneously with several synergistic advantages. The paper also considers the related potential impacts of pore space competition (with future groundwater use, gas storage and shale gas) on CCS expansion. Freshwater and brine must become key decision making inputs throughout CCS operations, building on existing successful industrial-scale integrations.

Keywords: CO_2 Capture and Sequestration, Water management, Brine production, Pressure management, Pore space competition

1. Introduction

Coal is currently the dominant source of baseload electricity production in many developed and developing nations. With projected worldwide electricity demand rising, the world's huge coal reserves are likely to continue to play a central role. Most projected climate change mitigation strategies to curb CO_2 emissions must consider the continued use of coal, and therefore must integrate technologies to allow simultaneous coal burning and CO_2 emission controls[1,2]. CO_2 Capture and geological Sequestration (CCS) in deep saline formations is currently the most viable of these technologies. Experience in Enhanced Oil Recovery (EOR) operations, as well as with CCS demonstration projects [3,4] has improved our understanding of CO_2 injection and management. Subsurface

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modeling capabilities have also been enhanced considerably [5,6]. However, to have a significant effect on atmospheric carbon emissions, the scale of CCS activities must be expanded by several orders of magnitude (fig. 3 in [7], [8]). Such an increase brings several challenges which are often summarized in four major categories: (I) CO_2 capture cost; (II) sequestration safety; (III) legal and regulatory barriers; and (IV) public acceptance.

Herein we propose an additional category of challenge across all CCS operations: water management. This includes management of both freshwater resources and brine. We suggest this new challenge for several reasons, namely: (1) a CCS retrofitted coal-fired power plant requires about twice as much cooling water as the original plant which may be accommodated by extraction and treatment of subsurface water; (2) brine extraction may concurrently allow for large-scale pressure management of both the injection formation and overlying reservoir; and (3) in regions with scarce water supplies and low salinity brine, extraction coupled with desalination may constitute a viable source of freshwater or "greywater" suitable for irrigation or other industrial processes. At present the interactions among freshwater extraction, CO_2 injection, and brine management are being considered too narrowly - in the case of freshwater almost completely overlooked- across CCS operations and the four challenge categories above in the CCS literature, debates and conferences. Active management of CCS operations through an integrated approach should address all these challenges simultaneously while also considering their interactions.

In this paper we begin by presenting an overview of freshwater, CO_2, brine, and pressure challenges, including considerations of the CCS scalability, pore space competition, and recent technological developments (shale gas and deepwater offshore drilling) that could impact future CCS operations. We then make the case for an integrated approach that includes resident brine production, treatment, use to address freshwater challenges, and partial re-injection. We finally present synergistic advantages and identify new questions that arise from an inclusive active management solution.

2. Freshwater, CO_2, brine, pore space, and pressure CCS challenges overview

Most of the challenges below have been identified separately but have not been viewed in a broader, integrated context. The challenges are presented here in a single framework to identify potential synergies. Figure 1 is a conceptual graphic comparing the same CCS retrofitted coal-fired power plant impacts under two scenarios: a passive CO_2 injection operation on the left side versus multiple active and integrated CCS operations on the right. The figure identifies **Challenges** posed by passive injection with red numbers (identified in the text as **X^C** and on the figure as X, where X is the number), **Synergies** associated with integrated management by blue numbers (**X^S** and X), and resulting new **Questions** that need to be addressed by black numbers (**X^Q** and X).

a. Increased water demand from CO_2 capture

An energy and water nexus has clearly been identified in the literature in the US[9-11], India, South-Africa, and Brazil [12] and in particular in China [12-16] where water saving methods in the coal industry are being considered [17]. In both energy production and industry, water is already a limiting constraint nationally and internationally as shown by recent coal plant siting problems, and litigation cases in both the domestic and international arena [18-20]. A coal-fired power plant requires very large water volumes for cooling processes [21-23]. (**1^C**) Water is an additional major challenge due to the considerable increase in water use for power plants including CCS. This is particularly significant when existing plants are retrofitted, due to increased cooling need in the regeneration process of expensive CO_2 capture chemical solvents (amines) [21,22,24]. Water scarcity will become accentuated with large-scale CCS expansion unless an active water management strategy is implemented [22,25].

b. CO_2 sequestration challenges

(**2^C**) Geochemical reactions between CO_2-acidified-brine and injection formation minerals might lead to injection capability reduction by decreasing its intrinsic permeability, and porosity [26,27]. (**3^C**) CO_2 or CO_2-rich-brine might corrode the sealing cement -if present- in the well segment perforating the aquitard. The resulting integrity loss increases upward leakage risk. (**4^C**) The high local pressure build-up resulting from injection can drive CO_2 (& brine) leakage via: natural faults; man-made active and/or abandoned wells [28]; up dip of a tilted injection formation; and/or by diffuse leakage through aquitards [29]. Leakage to shallow geological formations generates concerns of Underground Source of Drinking Water (USDW) contamination. (**5^C**) Leaked CO_2 potentially changes aquifer water chemistry due to its reaction with aquifer minerals, decreases in its pH, and increases its metal mobility and concentrations [30]. (**6^C**) Furthermore, brine leakage potentially increases USDW salinity. (**7^C**) Finally, CO_2 gas may leak in the vadose zone and diffuse into basements, which could present potential health hazards and require remediation [31,32]. (**8^C**) CO_2 plume tracking, monitoring, and accounting present their own set of challenges. (9[C]) Ultimately it will be vital to develop appropriate procedures to control the plume outer extent and be able to remediate if CO_2 unexpectedly appears in an undesired zone, such as a neighbouring production field or a densely populated area.

c. Injection formation/reservoir pressures and brine leakage challenges

Pressure challenges, starting at the injection well, span over very large spatial scales. (10[C]) At the injection well, injectivity -and hence storage capacity- are limited by the fracture pressure constraint. Operators are required by law not to increase the injection formation pressure above the overlying aquitard's fracture pressure to avoid rupturing it and hence creating open leakage pathways. (11[C]) Pressure is a main driving mechanism for both CO_2 and brine leakage. (12[C]) The outer extent of the pressure pulse reaches far beyond the CO_2 plume outer radius. The Area Of Review (AOR) concept is expected to be based on the largest spatial extent of the CO_2 plume or the "critical pressure" (defined as the pressure increase necessary to lift resident brine from the injection formation to the USDW) [33]. (13[C]) In order to obtain injection permits operators will have to demonstrate that they can accurately define, control, and minimize this AOR. To the authors' knowledge there is no publically available research of active AOR management and corrective measures by operators to achieve this despite the requirement in existing regulatory documents such as the directive of the European Commission on CO_2 storage (see Article 9, paragraph 6 and Article 16 of [34]). Studies considering the consequences of large-scale CO_2 injection at the basin scale are indispensable [35-39], but would be even more valuable if they included pro-active pressure release. Research has begun on possible leakage remediation and corrective measures and future work should consider the synergies presented below [40-43]. Finally, the potential for induced seismicity resulting from large scale CO_2 injection needs to be carefully taken into consideration [36].

d. Scalability challenge

The daunting challenge is to expand CCS operations from the current cumulative 1-10MtCO_2/y demonstration projects, to sequestration on the order of 100 MtCO_2/y by 2020, and 1000 MtCO_2/y by 2030 (see fig. 3 in [7], and [8]). Multiple operations will inevitably have to be built in a given geologic basin which, if not properly integrated, may operationally constrain each other. Determining the respective pressure build-up contributions, and CO_2 and brine leakage responsibilities, will be difficult unless an active management is put in place.

e. Competition for pore space

In addition to the challenges a)-d) it is important not to ignore the potential long-term competition for pore space which could greatly restrict the required CCS expansion. A 2009 report to congress by the US Department of Interior states that CCS "may potentially conflict with other [...] uses including existing and future [...] oil and gas fields, [...] and drinking water sources [...] These impacts need to be addressed" [44].

- **Future groundwater demand**

In the United States the Underground Injection Control (UIC) program protects any aquifer under the 10,000mg/l salinity threshold as USDW. The preliminary analysis of [45] concludes that competition concerns for CCS versus future demand for deep saline groundwater exceeding 10,000mg/l for public supply, agriculture, or industry "are likely to be warranted in limited select regions across the U.S., particularly in areas that are already facing water scarcity". This is a key research area to advance but it must include the facts that CCS sequestration operation competes for use of reservoirs that may supply future water demand; and, that the CCS capture operation will compete for use of surface water/subsurface treated water. The latter was not included in the preliminary analysis presented in [45].

- **Natural gas storage**

Demand for natural gas storage is increasing drastically [46-49]. The process is often referred to as a useful experience or technological analogue that CCS can build upon. However, CCS versus natural gas storage competition for pore space is rarely mentioned, at best simply acknowledged, and has not yet been quantified [44,46,50-54]. [54] and [46] present several gas fields as good candidates for CO_2 sequestration, acknowledge that benefits of enhanced gas recovery exist, but caution that irreversible CO_2 sequestration removes a given storage site for any other use whereas a cyclical gas storage reservoir may be used for CO_2 sequestration in the future.

- **Shale gas**

The recent shale gas boom in the US and around the world brings a pressing question concerning CCS. Will the competition between mutually exclusive shale uses -as a supply of gas following the destructive hydraulic fracture of its structural integrity in a shale gas operation versus as an intact protective seal preventing upwards leakage of CO_2 out of the injection formation in a CCS operation- restrict CCS expansion? These incompatible uses are clearly conflicting as shown in Figure 1a.

f. Sequestration safety: dynamic multiple wells remediation strategy replacing single static well

It is essential to remember that until late April 2010 there was public belief that offshore deepwater drilling could be done without any real risk. Building upon lessons learned in the recent failure of deepwater offshore drilling safety procedures CCS operational planning should consider a move away from a single static $MtCO_2$/y injection well. Pre-establishment of dynamic i*n situ* monitoring and potential remediation capabilities through multiple wells in the injection formation near the CO_2 plume, and pressure release wells located further afield to control the AOR may be desirable. Such additional well drilling and operations will carry a cost not included in current estimates.

3. Necessary integrated management

If the identified challenges are only thought of non-collaboratively by different research groups /companies, it will limit the exposure and knowledge transmission about their interactions and delay any global strategy to coherently address them. Even in the most optimistic scenario where key challenges could be addressed in isolation it might be insufficient due to factors not included in the design of that scenario like the current CCS operation paradigm overlooking the water challenge. Assuming that the capture cost of $1000MtCO_2$/y could become affordable by 2030, it does not guarantee that it can all be appropriately injected or safely sequestered. Even if we assume that $1000MtCO_2$/y could be sequestered by 2030 without brine or CO_2 leakage into USDW, and pressure pulse control could be achieved through pressure release wells to minimize the AOR, if the region considered does not have the available water resources to satisfy the additional cooling water need, or if freshwater withdrawal is too sensitive of a public issue, the project would not likely be implemented with billions of dollars in capital investment at risk. Synergies to address such issues will be proposed as integration opportunities below in section 4, keeping in mind the potential backfire cost and/or public acceptance consequences.

There are many examples of successful global integration in large scale processes both in the power plant and subsurface environments, such as: (i) EOR by-products (methane, CO_2, brine) instead of being vented or simply dumped in the local natural environment can either be treated and sold, or separated and re-injected to maintain the reservoir pressure and/or generate an enhanced sweep to get more valuable oil out of the ground; (ii) Combined cycle power plants or gas turbines by using otherwise-wasted-exhaust heat in an additional thermodynamic cycle allow significant overall efficiency improvement; (iii) coal-biomass-CCS strategies take advantage of both the high energy density of coal and the renewable characteristics of biomass which coupled with CCS perform as a CO_2 scrubbing electricity supply.

Globally integrated active management approaches have proven to be successful in different industrial-scale engineering projects and should similarly applied to CCS projects at the very early stage of science research, and then throughout the regulation, engineering and implementation, to address freshwater, CO_2, brine and pressure challenges.

Recently published articles have identified a freshwater challenge, along with National laboratory reports and conference presentations pointing toward a similar brine production concept [24,25,55-63]. A serious effort has begun in quantifying the feasibility and viability of treating the produced brine and using for cooling. First order economics indicate the positive potential of such concepts [55,56]. Air/Dry cooling systems exist and should be compared with water consuming ones [64].

Several CCS studies include or consider brine production wells solely to avoid pressure build-up. They are either not aware or not considering the presented challenges and the technical synergies described below in section 4 [24,35,43,65,66]. The increased water needs required for CO_2 capture is absent in all of them. However it is encouraging that the Interagency Task Force on CCS established by President Obama reported in August 2010 on both the CO_2 capture increased water need, and "Pressure management schemes, such as brine extraction […] to mitigate some of the basin-scale factors associated with wide scale deployment" even though synergies between the two were not established [60].

To address the presented challenges requires an integrated management -which represents a significant shift from the current CCS paradigm- including, but not limited to, the active production, treatment, use for cooling, and partial re-injection of brine as conceptually represented in Figure 1b. Several synergistic advantages of implementing such a solution and resulting new questions are described in the sections 4 and 5.

4. Synergistic advantages of active and integrated operations

The increased cooling water volume required annually for a standard 1GW coal-fired power plant CCS retrofitted is on the same order of magnitude, roughly 10 millions m^3 (Mm^3), as the emitted CO_2 volume to be sequestered. For context this amount of water would supply 1/3 of the annual drinking water delivered to Copenhagen (at 32.6 Mm^3 in 2005) [67]. The 235 Mm^3 annual withdrawals from municipal water supply wells from deep aquifers beneath the city of Chicago are of the same order of magnitude as the volume of CO_2 generated across the Illinois basin by dozens of coal-fired power plants [36]. These withdrawals resulted in a decrease of as much as 45m (0.45MPa) in the Mount Simon Sandstone potentiometric surface around Minneapolis, and by over 182m (1.8MPa) in the Chicago area. Other examples of fluid volume handled in different industries are presented in [66].

When considering active management to handle freshwater, CO_2, brine and pressure CCS challenges, several synergies are worth taking into account and should be further researched. These include: (1[S] synergy 1 in Figure 1b) Quantifying the potential benefits of brine production to free up pore volume for CO_2 sequestration, which would minimize both displacement of the equivalent brine volume out, and changes in potentiometric surface. This is an important area of future research. (2[S]) If brine pumping and treatment were considered in water scarce regions of coal dependent areas like the arid American Mid-West, both could potentially take advantage of the local pressure increase resulting from the CO_2 injection [55,56]. Produced brine will carry a significant heat, depending on the site-specific geological temperature gradient and the pumping depth, which can appear conflicting with its cooling use at first. An electricity generating geothermal unit taking advantage of this heat could cover part of the treatment plant energy penalty. Heat would need to be careful integrated in treatment process management because of both potential advantages (e.g. higher temperature could favors higher flux through Reverse Osmosis (RO) membranes, or could be used in high salinity brine thermal distillation) and disadvantages (e.g. RO membranes' internal support structure deforms more readily at higher temperature than 40-50°C reducing their operating lifetime) which need to be further researched [68]. El-Naas et al [69] investigated the potential use of the output from desalination plants ("desalination reject brine" in the paper) in the CO_2 capture process but neglected the increased water need. (3[S])Multiple injection/production wells strategies could also be used in a remediation situation where CO_2 has been detected in an undesirable neighboring field from which the CO_2 plume needs to be either "steered" away, and/or pumped and vented [42]. (4[S]) Brine treatment plant output (a saltier brine) needs to be appropriately disposed of. While an evaporation pond may present USDW contamination risks and regulation challenges, the re-injection of the more concentrated brine could be advantageous in several ways. Injecting it: in the former CO_2 injection well could help immobilize and dissolve all the CO_2 injected [40]; or, in an additional well located optimally could reinforce a steering effort of the CO_2 plume in a "push-pull" injector/producer wells pair strategy. Finally, re-injecting concentrated or normal brine in an overlying aquifer could create a beneficial hydraulic barrier through over-pressuring, thereby reducing leakage via fracture or wells and diffuse leakage across the caprock [41].

If brine is pumped out of the injection formation, it will: (5[S]) significantly reduce the outer extents of both the pressure pulse and critical pressure (AOR); and (6[S]) decrease the local pressure which will concomitantly lead to a decrease of CO_2 and brine leakage pressure drive and hence in the leakage risk. (7[S]) Remembering the fracture pressure constraint at the injection well, increased injection capacity could be realized by reducing local formation pressure. (8[S]) Smaller and more controlled pressure (avoiding shale fracturing and induced seismicity) and CO_2 footprints would allow multiple CCS operations in a single basin to co-exist without constraining each other, and also result in projects less prone to permitting, accounting, legal/insurance and public acceptance disputes. (9[S]) In the same way injection of CO_2 produces valuable oil in Texas via EOR, Enhanced Water Recovery could sequester CO_2 in the US Midwest -and other arid regions of coal dependent countries- producing valuable water (at a cost to be determined on a case by case basis) for other industrial and agricultural uses. (10[S]) A brine producing well, once reached by CO_2, could be turned into an in situ monitoring well and potentially later on into a CO_2 injection well. (11[S]) Proactive and integrated management and containment control -as opposed to passive CO_2 injection management with no in situ monitoring, control, and pressure release of the system- will inspire confidence to the public.

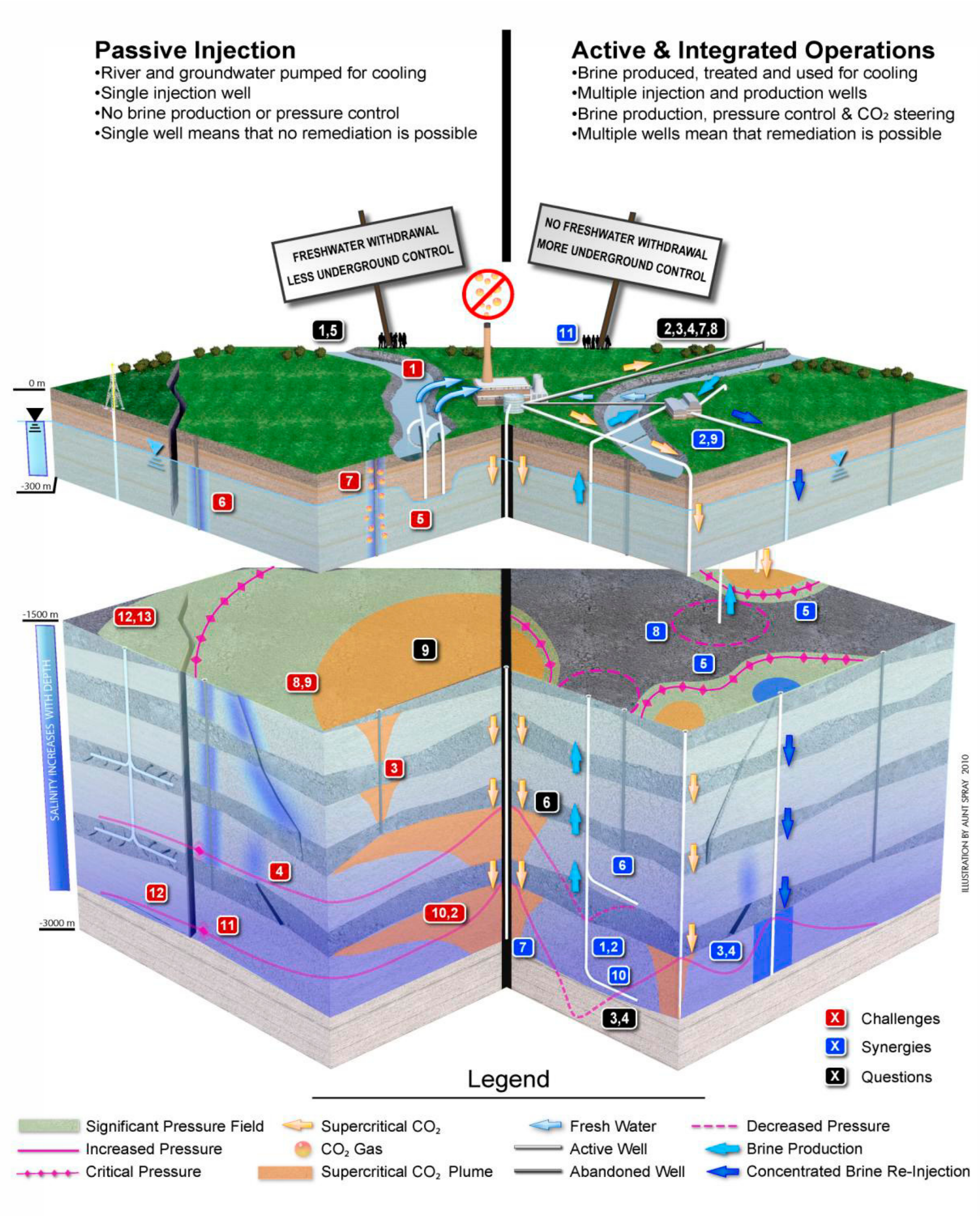

Figure 1: (a)(left) Current CCS operation paradigm challenges (X^C in Section 2) with power plant cooling water drawn from surface or groundwater, a single CO_2 injection well, and no pressure control/remediation strategy via other wells. (b)(right) Synergistic advantages (X^S in Section 4) of multiple active and integrated CCS operations including: multiple CO_2 injection wells, multiple brine production/re-injection wells -conceivably used for remediation-, a produced brine treatment plant, and treated-brine use for power plant cooling leaving the river and groundwater withdrawal-free.

5. Discussion

a. Integrated pro-active management research questions

This integrated proactive management of freshwater, CO_2, brine and pressure is a newly proposed process and will lead to a number of important questions, including the following: ($\mathbf{1^Q}$ Question 1 in Figure 1) Does the additional water demand for the worldwide projected CCS expansion match with projected available water supply? This is particularly relevant for the largely coal dependent nations [70] already suffering from restrained water in local regions; ($\mathbf{2^Q}$) What is the most environmentally friendly and cost-effective technical configuration to treat, use produced brine in power plant cooling, and dispose of the treatment plant's saltier output?; ($\mathbf{3^Q}$) If CO_2 reaches the brine producing well it not only defeats the enterprise's purpose but would it also prevent the treatment system from functioning?; ($\mathbf{4^Q}$) CO_2 might have changed water and brine chemistry to the point that it affects the technical feasibility or economic viability of a chosen brine treatment process. What technical solution could address this plausible scenario?; ($\mathbf{5^Q}$) Do relevant legal and regulatory processes exist to address this CCS additional water and brine disposal requirement? Will the cross-border/cross-state water dilemma [18-20,50] get worse or could a legal framework tackle it?; ($\mathbf{6^Q}$) How will the pore space ownership procedure and appropriation process be affected by this novel deep brine commodity previously considered valueless?; ($\mathbf{7^Q}$) Who will publish detailed integrated case studies that, (a) incorporate CO_2 capture and power plant cooling processes using produced brine, and CO_2 injection operations coupled with brine production, and (b) carefully quantify cooling water and energy cost (like [71]), sequestration safety, and public acceptance?; ($\mathbf{8^Q}$) How would the necessary local power plant water strategy evolve if the cooling water now comes from the CO_2 sink geographic location?; ($\mathbf{9^Q}$) Does the industry have the CO_2 remediation capabilities and has it agreed with regulatory authorities on emergency procedures to pump and vent the CO_2 out of danger zone in case of a natural or human health hazard threat?

b. CCS community challenge

It is imperative to take a step back and note why some challenges are not reaching the wider CCS community. The breadth, depth and level of complexity of each are such that specialisation in a given field is needed to conduct research on or solve any of them. Therefore it has been logical to consider these challenges piece by piece in isolation to adequately address each issue. But focused research can result in a lack of cross-disciplinary communication and vision. In other words, considering the challenges in isolation, even if necessary to allow their resolution, could turn out to be unproductive due to key challenges being ignored. An integrated approach would address and resolve multi-disciplinary issues while capitalizing on synergistic opportunities and prevent any of the challenges identified in this work from becoming barriers to CCS development.

c. Future work

Technical results will be published in a subsequent article that will focus solely on the conjunctive use of saline aquifers for CO_2 sequestration and water supply for power plants. The impact of injection-withdrawal coupling on the CO_2 injection plume, the pressure field, CO_2 and brine leakage risk will be quantified using a range of simulation codes from Schlumberger's full numerical ECLIPSE model to a simplified analytical model, in an effort to complement the useful work by Buscheck, Hao et al [63] and LeGuenan, Rohmer et al [32,41,43].

6. Conclusion

Our society is highly coal dependent [70]. Holding the increase in global temperature below 2°C to avoid climate-tipping elements and unmanageable changes will require stabilizing CO_2 concentration below about 450ppm during this century in addition to carefully and comprehensively dealing with non-CO_2 greenhouse gases, black carbon and aerosols as laid out by [72]. Fundamentally the only solution to achieve a very large CO_2 atmospheric emission reduction is to move toward phasing out coal burning and replace baseload electricity production with non-carbon intensive resources as soon as possible. However, because coal is a cheap, geographically and geopolitically well-distributed resource it is currently economically and politically unrealistic to stop using it. CCS is going to be a vital element of any strategy to stabilize CO_2 atmospheric emissions.

The comprehensive overview of freshwater, CO_2, brine, pore space and pressure challenges across CCS operations structured here in a single framework identified that an integrated approach needs further research to avoid overlooking critical challenges that may become major obstacles to CCS implementation. Synergistic advantages of such proactive integration were identified in this work, in addition to new questions arising from its implementation. Furthermore we argue that freshwater and brine must be linked to CO_2 and pressure as key decision making inputs throughout CCS operations while recognizing scalability and potential pore space competition challenges. A detailed technical or cost analysis investigation of integrated CCS development presented herein is outside of the scope of this short paper, but the authors strongly believe that it is crucial to initiate and constructively examine early stage CCS developments for synergistic opportunities before large-scale expansion.

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