Geological carbon sequestration options in WA
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Introduction

This short piece, adapted from a presentation to industrial players in the state of WA, outlines some of the geologic sequestration options for facilities in the state. This is intended as a rough outline, not a comprehensive treatise.

Geological sequestration in a nutshell

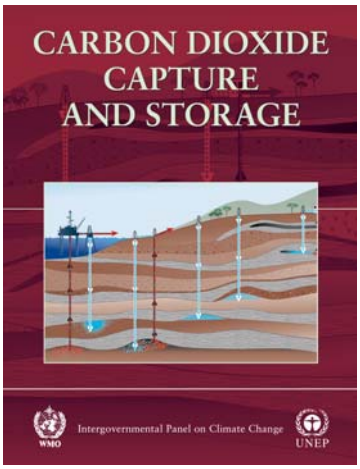
Regardless of the geological medium or the type of the candidate reservoir, the following factors are paramount when considering sequestration of CO2 in geologic formations:

- **Capacity:** (how big is the reservoir?) the target reservoir needs to be able to accommodate the quantities of CO2 that will be injected over the lifetime of a project or facility. A reservoir's capacity will depend on the porosity and thickness of the rock formation.
- **Injectivity[1]:** (how easily and at what rates can we inject in the reservoir?) the target reservoir needs to be able to withstand the sustained CO2 output from the generating source, which for baseload power plant will be fairly constant, without exceeding certain thresholds such as injection pressure and without fracturing. "Clogging up" of a reservoir would lead to the emissions from the plant having to be vented.
- **Effectiveness/risk:** (will the CO2 stay sequestered?) CO2 gets trapped into different rock formations through a variety of trapping mechanisms that depend on the rock itself. These mechanisms tell us a lot about how likely or unlikely it is for the CO2 to remain permanently in the reservoir. Additionally, the layout of the rock formation itself affects the effectiveness of the sequestration through the presence or absence of transmissive faults that might provide leakage pathways for the CO2, or through the presence of caprocks that would act as further barriers to the CO2 migration, reinforcing other trapping mechanisms.
- **Economics:** even if a reservoir has sufficient capacity, injectivity and would effectively trap the CO2, the engineering and operational costs need to be examined to ensure that they are acceptable.

[1] Injectivity characterizes the ease with which fluid can be injected into a geological formation and is defined as the injection rate divided by the pressure difference between the injection point inside the well and the formation.

All of the above parameters can be predicted and measured accurately through well established methods and techniques: we are in possession of a considerable body of knowledge, operational experience from sequestration and related activities!

Sequestration in sedimentary formations: today's technology or tomorrow's aspiration?



Research on Carbon Capture & Storage (CCS) has been taking place for many years now, with major international conferences taking place since the early 1990s. Since then, our knowledge on the subject has greatly expanded, to the extent that the Intergovernmental Panel on Climate Change (IPCC) issued a special report on CCS in 2005. There is a substantial body of evidence, knowledge and peer-reviewed literature on CCS that enables us to speak with authority on the subject today. In many cases, we can speak with a very high degree of confidence. We can also identify the areas where that is not possible, and where additional research is needed.

In many ways, CCS is not new. All three stages (capture, transportation and sequestration) have been demonstrated and operated in large, commercial scale installations.

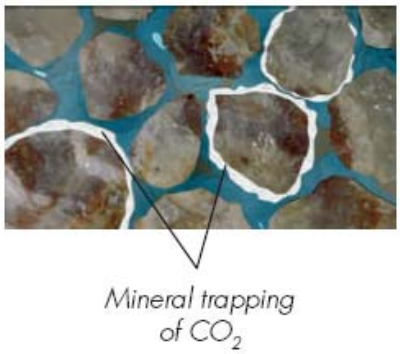
Regarding transportation, pipelines today operate as a mature market technology and are the most common method for transporting CO2. The first long-distance CO2 pipeline came into operation in the early 1970s. In the United States, over 2,500 km of pipeline transports more than 40 million tons CO2 per year from natural and anthropogenic sources, mainly to sites in Texas, where the CO2 is used for Enhanced Oil Recovery (EOR).

Source: International Energy Agency

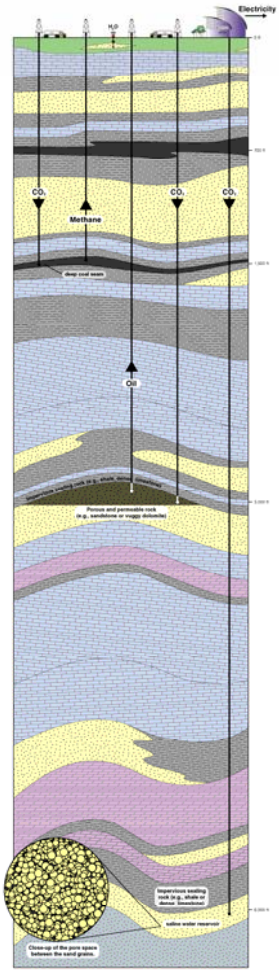
Some 35 million tons CO2 annually are injected in mature oil reservoirs for the purposes of EOR, a practice that has been around for several decades. The CO2 aids in retrieving oil that is otherwise stranded in reservoirs, which would be near the end of their economic life without such advanced techniques. Although the objective in this process is to maximize oil yields and not to sequester CO2, the two processes are fundamentally similar and share much of the same operational engineering.

Moreover, several commercial and research projects worldwide capture and/or inject CO2 in sedimentary geological formations. Of these, three stand out because of their scale and their widely publicized results: Sleipner in Norway, Weyburn in North Dakota/Canada and In Salah in Algeria. These projects have been operating since 1996, 2000 and 2004 respectively, and have been studied intensely. The results are showing that there is no reason to expect any CO2 leakage from these projects, and that the injected volumes are very likely to remain permanently sequestered in their respective reservoirs.

The projects just mentioned give us a great deal of confidence that CO2 can remain permanently sequestered in geological reservoirs. There are multiple trapping mechanisms for CO2. *Residual trapping* limits CO2 mobility in a formation through capillary forces, much like a sponge holds air that has to be squeezed out to let water in. *Solubility trapping*, whereby CO2 dissolves in the formation fluids, ensures that the CO2 is no longer buoyant and therefore tends to sink rather than rise towards the surface. *Stratigraphic trapping* occurs when overlying, impermeable rock formations prevent any upwards movement of CO2 from the underlying reservoir rock, effectively acting as lids. Appropriately selected injection sites will possess several layers of such caprocks, and thus multiple reinforcements to the other trapping mechanisms. Finally, *mineralization trapping* takes place when the CO2 over time forms carbonate minerals and essentially becomes part of the solid rock into which it was injected.



Source: International Energy Agency



A stratigraphic cross section of the Illinois Basin, showing multiple layers of caprock (grey). Source: Illinois State Geological Survey and the Midwest Geological Sequestration Consortium)

The IPCC report concluded the following:

"Observations from engineered and natural analogues as well as models, suggest that the fraction retained **in appropriately selected and managed geological reservoirs** is very likely to exceed 99% over 100 years and is likely to exceed 99% over 1,000 years. For well-selected, designed and managed geological storage sites, the vast majority of the CO2 will gradually be immobilized by various trapping mechanisms and, in that case, could be retained for up to millions of years. Because of these mechanisms, storage could become more secure over longer timeframes". (emphasis added)

In support of that statement, a recent MIT study[2] concluded that:

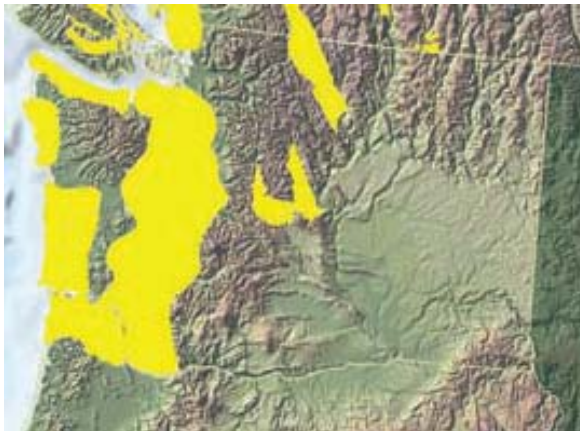
"Although substantial work remains to characterize and quantify these mechanisms, they are understood well enough today to trust estimates of the percentage of CO2 stored over some period of time – the result of decades of studies in analogous hydrocarbon systems, natural gas storage operations, and CO2-EOR. Specifically, it is very likely that the fraction of stored CO2 will be greater than 99% over 100 years, and likely that the fraction of stored CO2 will exceed 99% for 1000 years. Moreover, some mechanisms appear to be self-reinforcing. Additional work will reduce the uncertainties associated with long-term efficacy and numerical estimates of storage volume capacity, but no knowledge gaps today appear to cast doubt on the fundamental likelihood of the feasibility of CCS".

The remaining 1% is a number reserved by the IPCC to take into account any insignificant amounts of CO2 that might be vented during the operation of sites due to human factors over those very long periods, and does not reflect reduced confidence in the underlying geology or the ability of formations to retain CO2. There is every possibility that even this tiny fraction will not

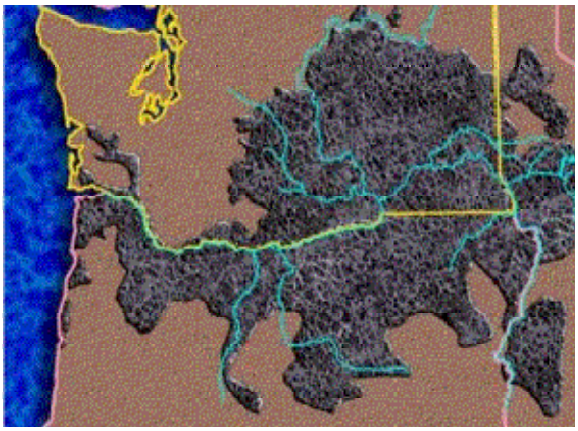
[2] "The Future of Coal – Options for a Carbon Constrained World". An Interdisciplinary MIT Study, 2007.

reach the atmosphere with proper site operation and regulation, bringing the total retained fraction to 100%.

Leakage is possible, but is unlikely for good sites, generally predictable, can be detected and remedied promptly, and is extremely unlikely to be of a magnitude that would endanger human health and the environment **if the project is performed under adequate regulatory oversight and according to best practices**. After all, it should come as no surprise that the same types of reservoirs that have stored hydrocarbons for millions to hundreds of millions of years, as well as naturally occurring CO2, are also capable of retaining CO2 injected by humans.



Deep saline formations in the WA area
Source: NATCARB



Extent of the Columbia river basalts
Source: USGS

Sequestration in basalts

Basalts are crystalline and glassy rocks with abundant iron, calcium, and magnesium rich silicate minerals. When these minerals are exposed to carbonic acid over time, they preferentially form new carbonate minerals, releasing silica while permanently binding CO2. Basalt formations therefore have the potential to sequester quantities of injected CO2.

Sequestration in basalts is a worthwhile research area, and the Pacific Northwest National Laboratory is pioneering efforts to expand our knowledge on the topic. However, sequestration in basalts is a different ballgame to sequestration in deep saline formations, oil fields or gas fields, where the vast majority of our experience and knowledge resides.

Presently, there are outstanding questions regarding large-scale injection in basalts:

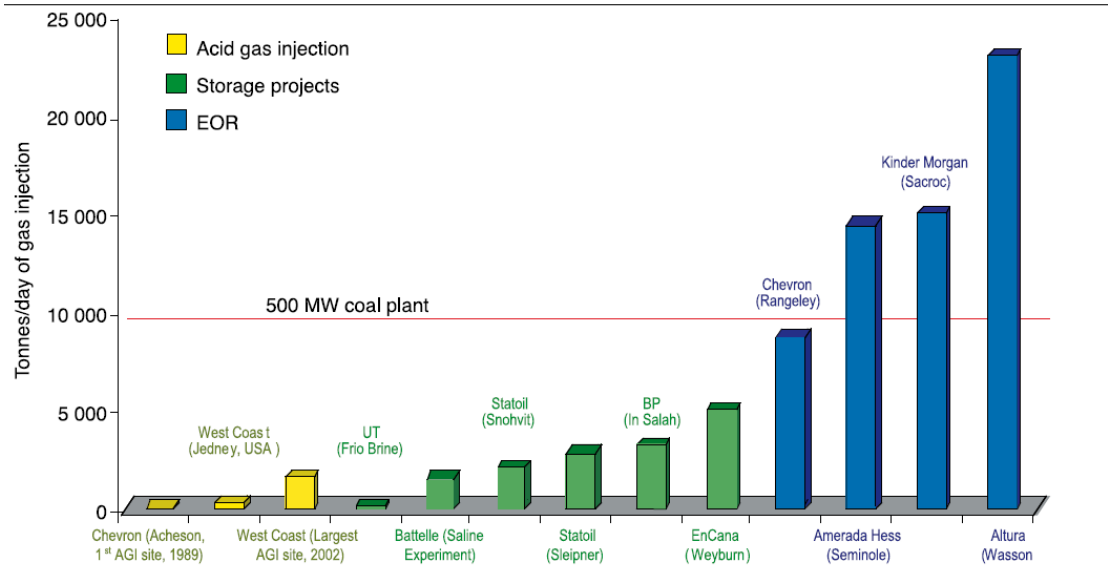
- **We are not yet in a position to establish that CO2 injected in basalts will not leak.** Basalt commonly has low porosity, low permeability and low pore space continuity. Any permeability is generally associated with fractures through which CO2 may leak unless there is a suitable caprock. In other words, the CO2 would not be injected into the rock framework itself, but into fracture networks that are part of the overall rock formation. Establishing that these networks themselves will not lead to the surface is difficult, and evidence so far is inconclusive. Perhaps most importantly, we would be in uncharted territory when injecting such volumes of CO2 in basalts: there is no relevant industrial experience or knowledge as to how the formations would respond when pressurized.
- **The evolution of the CO2 plume once injected in the basalt cannot currently be predicted** with the same accuracy or precision as in sedimentary rocks. This adds uncertainty to the efficacy of an operation, and to the credibility of a “sequestration plan”.
- **Monitoring the CO2 once injected in the basalt is problematic.** Well-established methods that have been developed for sedimentary rocks do not lend themselves to use

in basalts. Seismic monitoring, for example, becomes problematic because it is difficult to distinguish the CO2 in a high velocity, fractured medium such as basalt. Experiments with tracers have also highlighted problems.

These considerations led to IPCC to conclude that "[b]asalts may locally provide niche options for geological storage of CO2". It would not be advisable in our opinion to consider sequestering large volumes of CO2 in basalts in the context of ESSB 6001 timelines and requirements. The unanswered questions on the efficacy of such an operation would present too large a physical, business and regulatory risk. State agencies might want to consider, however, cooperating in the ongoing research on CO2 sequestration in basalts as a side operation, to aid progress on that front.

Sequestration options in deep saline formations

A typical 2-6 million tCO2/yr that a power plant would have to sequester lies in the range of the larger injections that have been carried out so far, either with sequestration as an aim, or for enhanced oil recovery. For typical geologies, 1 million tCO2/yr is an approximate estimate of the minimum injection volume of CO2 that would be sufficient to exceed critical geological thresholds, and as such to be able to predict the response of formations to larger injected volumes. The Sleipner, Weyburn and In Salah projects are all in the region of 1 million tCO2/yr, and as can be seen from the figure below, larger injections have been performed in EOR operations. Such injection volumes would not push the boundaries of existing knowledge or operations.



Source: IPCC

Are there suitable reservoirs to accommodate the emissions in the state? There are two main options to consider:

- **Option I:** West of the Cascade range, there are identified saline formations in the Central Washington Basin that could prove suitable.
- **Option II:** East of the Cascades, there might be suitable reservoirs under the flood basalts.

If suitable reservoirs were identified in those regions, CO2 could be sequestered using the same techniques that are used in other sequestration operations worldwide.

Required steps

Finding a suitable site

The most crucial aspect of a sequestration operation is to choose a good site that has adequate capacity, injectivity and seal integrity. In that respect, surveys would need to be carried out under both options mentioned above. The surveys could be done in a step-wise fashion as follows:

- An initial paper study summarizing existing knowledge and data could be conducted as a first step – approximate cost $200,000, duration 4 months.
- A broad geophysical survey of the regions in Option I or Option II would build on the initial study and utilize a variety of methods to obtain more detail – approximate cost $1-3 million, duration 9 months. This would probably include some combination of aeromagnetic, gravimetric, 2-D and 3D reflection seismic surveys, and would identify the thickness of viable strata, the structure of primary storage units, and the location of potential geological hazards (e.g. large faults).
- Using the results of the survey, detailed data could be obtained for the most promising reservoirs using seismic methods (to reveal the spatial and geographical characteristics) or through drilling wells (to reveal the porosity, injectivity and geochemistry of the formations) – approximate cost $1-4 million for a seismic survey or per well, duration 1 year.

Option I is more straightforward, since more is known about the saline formations west of the Cascades, and a detailed characterization of those sites would not entail drilling through the basalt body, which can be slower and more costly. Option II is nonetheless also viable, and could be used as an alternative plan – the additional technical complexity of drilling through the basalts is by no means insurmountable, and the added development and operational costs would still be small in comparison to the capital investment for a plant (that would be on the order of billions).

The results of such a staged approach would be of public benefit. Although the entirety of these services could be provided commercially, we believe that there is a case to be made for state assistance in these efforts, given that they will be revealing resources that would aid the state to meet its emissions performance standard and its greenhouse gas targets. The studies could be handled by the University of Washington, the State Geological Survey, the Pacific Northwest National Laboratory and the DOE regional partnerships.

Moreover, this staged approach, especially if carried out as a state-assisted public-private partnership and/or in conjunction with other proposed developments, could constitute part of a robust sequestration plan as required by ESSB 6001 that would enable a project to proceed in accordance to planned timelines.

Conclusions

- Geologic sequestration technology and know-how are well proven and established enough to be used today.
- The preferred geologic medium in WA is deep saline formations – large volume sequestration in basalts is not ready for commercial-scale applications yet.
- In compiling a sequestration plan, entities can engage in a step-wise investigation of geologic and technical options at a modest cost.
- Such an investigation would arguably be of public benefit and could be performed as part of a public-private partnership, possibly with state assistance.

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