Audience Q&A Continued

Disclaimer: These responses are from Jens Birkholzer, and do not reflect the viewpoint of Lawrence Berkeley National Labs or the U.S. Department of Energy.

1. **How does all this transport and deep injection of supercritical liquid CO2 compare in expense and hazard to reacting materials to solid carbonates and transporting sequestering those?**

   Great question. I don't have hard data or analysis on this, but keep in mind that CO2 needs other minerals to react with (so you need to grind rocks for example and have them react with CO2). If you then sequester the CO2 plus the rocks, you have gigantic volumes that need to be stored away somewhere. Compressing CO2 and injecting it as a liquid into the deep subsurface requires less volume. That is why carbon removal technologies who use reactive rocks to catch the CO2 from air will not store their reactive materials after CO2 has been captured. Rather, they will heat the rocks to "free" the CO2 from the reactive surfaces, capture that CO2, and typically store it as a liquid underground. The reactive rocks are then re-used for carbon removal.

2. **Are all of the pilot programs and research considering how the storage itself affects the environment and local health? i.e. What does the type of storage interact with in its environment, by what properties, and how will that change with CO2 storage? (e.g. thinking about how limestone filters groundwater and will be "plugged up" with CO2 mineralization, decreasing groundwater reserves and increasing likelihood of landslides, etc.)**

   Sounds like this question assumes that CO2 is stored near the environment or near groundwater. It is not. Typically our storage reservoirs are thousands of meters deep, where there are no usable water resources.

3. **Are there examples of CO2 storage or transportation from elsewhere in the world that are being done safely and have strong safeguards? Where and how much has been successfully sequestered?**

   Yes, there are many. My talk showed the example of Sleipner in Norway which started in 1996 and injected one million tons or so per year. Still going on and still safe. For a full overview check this report that was just published by the Global CCS Institute: *https://www.globalccsinstitute.com/resources/global-status-report/*

4. **Can you provide an assessment of how likely and dangerous CO2 storage in the Central Valley is on a scale from 1 to 10 with 10 being highly likely and dangerous. (I realize this is a generalization but I would like to have an overall idea).**

   This is a loaded question, but let me try (and note this is my personal opinion). Based on my research and general knowledge, I firmly believe that well-characterized sites and well-monitored sites (as required by the regulation) are safe. When it comes to leakage from the deep reservoirs into groundwater or surface, I feel the risk of actual harm to humans or environment is 1 out of 10. The probability is low and the hazard of some CO2 leaking out and up is quite low too. For induced seismicity, I give a 2 out of 10, mostly because predicting earthquakes is hard! I prefer storage reservoirs that are not *immediately above the deep crystalline basement (because that is where most large earthquakes occur).*

5. **What are the impacts of CO2 injection on groundwater acidification?**

   CO2 dissolving into groundwater reduces the pH. The presence of CO2 in itself is not a concern for groundwater quality but change in acidity could cause the release of naturally occurring contaminants that are otherwise bound to the minerals. We did some studies in the past, and in our field experiments we saw limited and rather short-lived impact on groundwater quality. In our field study, drinking water standards were not violated although we directly injected CO2 into groundwater.

6. **Who's looking at the Title 6 civil rights implications of all these Class 6 UIC permit projects considering none would exist without Dept of Energy, Dept of Trans federal dollars enabling them?**

   No answer.

7. **The existing geologic sequestatration…how much is currently being stored? And at what cost? What is the cost per ton being stored?**

   I don't have these numbers available to me right now. The current operating CO_2 capture capacity is 51 million tons per year, and much of this would presumably go into storage.

   The cost of storage is typically much less than the cost of capture, pressurization, and transportation. I don't recall exact numbers, and they decrease as technology matures, but I vaguely remember total storage costs of perhaps $20 - $50 per ton of CO2.

8. **How energy efficient are the various types of CDR? Say KWh/ton CO2 for removal vs KWh/ton CO2 when it is burned for energy ?**

   This is a question for a CDR specialist.

9. **How are you accounting for changes in thermodynamics as they relate to global convection currents?**

   I don't understand the question.

10. **Who is responsible for ongoing durable storage assurance monitoring when industry is shut down?**

    Good question. Some States have liability frameworks in place but not all.

11. **Are the regulations for CO2 geologic sequestration similar or different from fracking regulations?**

    Yes, they are quite different. The Class VI regulations for geologic storage are more stringent than those for fracking. And some States, including California, may decide to add to the Class VI requirements. CARB already does this within its Low Carbon Fuel Standard framework, where they require 100 years rather than 50 years of monitoring after injection ends.

12. **Did I hear correctly there are thoughts of sites in the Delta in Calif.?**

    Yes, there are a few pending permit applications in the deep sediments of the Sacramento Delta.

13. **What is the cost reserve to monitor (the S) - relative to the costs of the CC?**

    The monitoring cost varies widely depending on the site conditions and requirements. But in general, monitoring for storage is a small percentage of overall carbon capture cost.

14. **The presentation by Dr. Birkholzer featured a traffic light decision process. Who would be making the decision about whether to go from Green to Red? The operator obviously has an economic incentive to not shut it down. If the project owners/managers had to live in the area, would there be an additional incentive to make sure that it is run safely?**

    Not sure. Typically these traffic light systems are discussed beforehand between the operator and the regulator, so it is NOT a matter of negotiating a decision when the time comes. It should be pre-defined. Say for example, the traffic light is defined to go to red when a seismicity measurement is above M = 2, then the next steps should also be pre-defined, e.g, injection needs to stop immediately.

15. **For marine CDR the standard for durability is often 1,000 years! Why does CCS get off the hook after just 50 yrs?**

    CO_2 storage is supposed to be permanent. The 50 years is just the monitoring period after injection ends. Because CO_2 gets trapped by increasingly more trapping mechanisms and pressure decreases after injection ends, the storage risks decrease as well. Therefore the regulation assumes that 50 years of post-injection monitoring is sufficient.

16. **Since you state it migrates, how do we know it does not migrate to areas where geologic safety seals do not exist. We know gas will find a place of least resistance which would make it prone to leakage into the atmosphere?**

    CO_2 migrates laterally but with adequate trapping in place it will not forever and not very far. Projects will only be permitted if the seals are continuous and are regional enough to always encompass the region where future CO_2 might migrate. Plus a safety cushion!

17. **What are the dangers related to earthquakes disrupting storage of geologic CO_2?**

    As I pointed out in my presentation, there are two possible concerns about injection-related pressure buildup in the subsurface.
    - *Faults that are earthquake prone may be pushed to rupture by increased fluid pressure from CO_2 injection, which can occasionally generate seismicity. As long as that seismicity stays small, there is no harm; most of the time, it would not be felt at all. There is a possibility (not a large one) that sizable earthquakes could*

be generated, of a magnitude that could cause ground shaking or even damage at the surface. To reduce the earthquake risk, I prefer storage reservoirs that are not immediately above the deep crystalline basement (because that is where most large earthquakes occur).

- *Such large earthquakes are not typically expected to disrupt the storage of CO2 because they typically occur in the deep basement rocks, deeper than the storage reservoir.*
- *Much smaller fault rupture may occur in faults within the sealing units above the storage reservoir. Such faults are rare and if they exist they are typically impermeable. If injection pressure increases above a threshold, such faults could open and perhaps allow fluids to migrate.*
- *Because we understand fault activation mechanisms, we can define the pressure increase that can be allowed without causing earthquakes. The projects need to be managed such that they stay below such pressure thresholds.*

18. What happens if there is an earthquake?

See above.

19. Would increased seismic activity cause increased migration of the CO2 toward a fault which is a crack/space between the tectonic plates which could imply an easy place for leakage directly back into the atmosphere?

The seismic activity would not necessarily cause CO2 to migrate toward a fault. It is more likely that the injection-pressure increase provides a driving force for CO2 to migrate laterally under the seal. If then the CO2 encounters a fault within the seal, it could in theory migrate upward. But most faults within such sealing units are in fact close to impermeable (filled with shaly materials), so they would not allow flow.