Air Resources Board's Carbon Capture and Sequestration Program:
2016 Progress and Future Plans

Introduction

Carbon capture and sequestration (CCS) is an important strategy to reduce greenhouse gas (GHG) emissions and mitigate climate change. However, without a robust California specific accounting framework, CCS projects have not yet been able to participate in California's climate programs. In this paper staff will cover the following content:

- Overview of CCS and its benefits;
- California's climate programs;
- Primary challenges to implementing CCS projects;
- CCS program staff activities and milestones;
- CCS technical discussions, and staff literature reviews;
- How staff plans to integrate CCS into California's climate programs and the particular difficulties in doing so for each specific program;
- Next steps.

Background on CCS

CCS is a process by which large amounts of carbon dioxide (CO_2) are captured, compressed, transported, and stored in geological formations. CO_2 sequestration occurs by injecting captured CO_2 into geologic formations such as active or depleted oil and gas reservoirs, or deep saline formations. Alternatively, the captured CO_2 can be used in industrial processes such as construction materials, plastics, or fuel production. This alternative method is known as carbon capture and utilization (CCU), which, rather than leading to permanent sequestration, may result in avoidance of emissions of CO_2 to the atmosphere. Moreover, CCS is distinct from biological sequestration[1], which is typically accomplished through forest and soil conservation practices that enhance the sequestration of CO_2 (such as restoring forests, wetlands, and grasslands) or reduce CO_2 emissions (such as reducing agricultural tillage and suppressing wildfires).

Studies by the Intergovernmental Panel on Climate Change[2] (IPCC) and the California Council on Science and Technology[3] (CCST) have shown that CCS has the potential to reduce carbon emissions by billions of metric tons, and may be an integral part of meeting California's climate goals in 2050. CCS allows for existing fossil fuel resources, such as natural gas, to be used in a way that is much lower in carbon emissions than their use without CCS. Due to the potential importance of CCS in meeting California's long-term climate goals, Air Resources Board (ARB) plans to integrate CCS into its

---

[1] Sometimes referred to as "terrestrial sequestration".

[2] IPCC, 2014, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

[3] CCST, 2011, California's Energy Future: The View to 2050.

climate programs in compliance with the AB 32[4] requirements that GHG emissions reductions achieved are real, permanent, quantifiable, verifiable, and enforceable.

California's Climate Programs

California's climate programs include two market based programs that can provide GHG reduction benefits to CCS projects, the Low Carbon Fuel Standard (LCFS) and the Cap-and-Trade regulations. However, the mechanisms by which these programs reward GHG emissions reductions are different. Under the LCFS, CCS projects could generate credits for (1) fuel producers under tier 2 pathways, (2) crude oil producers under the innovative crude provision, or (3) refiners under the refinery investment credit provision. Under Cap-and-Trade, CO_2 suppliers (the capture facilities) could reduce their compliance obligation through the use of CCS. Both of these regulations require further actions by ARB before CCS projects can receive climate benefits, as both regulations require projects to use a board-approved quantification methodology (QM) to determine GHG reductions.

Staff is currently developing a QM for CCS under the Cap-and-Trade and LCFS programs. The CCS QM may be adopted for use in the Cap-and-Trade and LCFS programs as determined appropriate in rulemaking(s) specific to these programs. The QM will build upon the work of the California Carbon Capture and Storage Review Panel[5] (Blue Ribbon Panel), WESTCARB[6], and other organizations with extensive stakeholder engagement and inputs. The QM addresses accounting issues under AB32, but other requirements for a robust CCS program (e.g. site selection and certification, well integrity requirements, monitoring plan development) must be included using a protocol to ensure the permanence of sequestration. Therefore, staff plans to produce a Geologic Carbon Storage Permanence Protocol (thereafter referred to as Permanence Protocol) in addition to the QM for CCS projects.

Staff's initial CCS work will focus on geologic sequestration, consistent with existing ARB climate regulations, recognizing that the permanence and potential of CO_2 utilization will require additional analysis. The CCS QM and Permanence Protocol will establish procedures that accurately account for GHG emission reductions and provide confidence in the permanence of those reductions. While the CCS QM and Permanence Protocol will need to be comprehensive and rigorous, they will also need to retain some flexibility due to the site specific nature of CCS projects.

Staff has identified the following design principles for the development of the CCS program, and for integrating CCS into ARB's climate programs:

- Protection of public health and the environment;
- Robust GHG monitoring, reporting, and verification that ensure reductions are real, permanent, quantifiable, and enforceable;
- Focus on leak prevention;

---

[4] Assembly Bill 32, The Global Warming Solutions Act of 2006, AB 32, Statutes of 2006, Chapter 488.
[5] http://www.climatechange.ca.gov/carbon_capture_review_panel/
[6] http://www.westcarb.org/

- Based on sound science;
- Model program for use in other regions.

CCS Project Challenges

While some challenges of CCS projects are unique, such as the need to inject CO_2 into geologically appropriate areas deep underground, other challenges of CCS projects are more familiar to proponents of new technology, namely those of an economic and technological nature. In this section, staff provides an in-depth analysis of challenges, and how they may be addressed. Some of the solutions to these challenges may be addressed as part of the QM efforts, others may require different mechanisms, such as new policies or technology development.

One of the main challenges to CCS projects is geology. CO_2 injection can only be done in locations where the geology is appropriate. Studies have concluded that there is sufficient pore space available in California to inject tens of billions of metric tons of CO_2[7]; however, each site must be analyzed independently for whether the pore space is contiguous, economically viable, and capable of permanent CO_2 sequestration. The CCS QM and Permanence Protocol will have the flexibility to allow considerations of the unique characteristics and risk of individual sites.

Another challenge that CCS projects face is that of economics. Carbon capture and compression are frequently cited as the primary contributors to CCS cost. The capture cost per metric ton of CO_2 has been reported in the range of $30 to $110[8,9] depending on the type of facility and the technology used. Capital costs for new facilities can increase with CCS by 25% to 90 % above the cost of an equivalent facility without CCS[10], which can translate to anywhere between millions to a billion dollars.

Without incentives, facilities have little economic reason to incur CCS expenses. Many projects have been unable to overcome these costs, and some facilities that are currently engaging in CCS are even concerned that they will need to cease injection if reliable incentives are not forthcoming. The CCS QM and Permanence Protocol will be designed to allow CCS projects to take advantage of the incentives of California's climate programs, provided that these projects can meet the requirements. Additionally, economies of scale and technology advancements can reduce the costs over time. Reliable, long term investments to advance technology, and stable incentives will be needed to achieve economies of scale and GHG reductions from CCS projects.

---

[7] National Energy Technology Laboratory, U.S. Department of Energy, Carbon Storage Atlas: Fifth Edition, September 2015, Pages: 110.

[8] E.S. Rubin, J.E. Davison, H.J. Herzog, "The cost of CO2 capture and storage," International Journal of Greenhouse Gas Control 40 (2015): 378–400.

[9] Proceedings of CCS Cost Network 2016 Workshop, March 23–24, 2016, Cambridge, Massachusetts, USA.

[10] Report of the Interagency Task Force on Carbon Capture and Storage, produced jointly by the U.S. Department of Energy and the U.S. Environmental Protection Agency, August 2010, pg. 33-34.

Technology and economics are inter-related. Capture technology in particular is very energy, and hence cost intensive. Current commercial and demonstration scale projects are using capture technologies such as amine based solvents that will likely need to be further improved and perhaps even replaced with less expensive, more efficient capture technologies prior to wide deployment of CCS. Technology could be improved by public and private investment into CCS research programs. Additionally, demonstration projects bringing lab scale technology to larger scale can advance the availability and lower the cost of advanced technologies.

Given the technical and economic challenges, staff is exploring the concept of a pipeline network and injection hubs, where a network of pipelines would connect CO_2 sources to appropriate injection sites in order to reduce CCS costs and complexities. Incentivizing early actions in geologically appropriate areas may help decrease transportation costs of later CCS projects if pipeline infrastructure is built and can be utilized by those projects.

Other challenges are related to the risks of leaks and induced seismicity, and preventing potential negative health and environmental effects due to leaks and induced seismicity. Extremely high CO_2 concentrations in enclosed or poorly ventilated areas can cause acute health impacts. According to National Institute for Occupational Safety and Health (NIOSH) guidelines, CO_2 concentration at greater 4%, is considered dangerous to life and health, which is 100 times the ambient concentration of 0.04%. Low concentration of CO_2, as naturally exists in air, does not harm human health and other biological life. The CO_2 concentration in air is very low, and CO_2 mixes and disperses rapidly in air. In most cases, potential leaks associated with CCS to air are not considered a health concern in an open field or well ventilated structures.

CO_2 concentrations greater than 10%-20% in soil can negatively impact plants, and elevated CO_2 concentrations in aquifer may lead to degraded water quality, and increased acidity and metal concentrations. However, the risks of such negative leak impacts are low, and the potential negative impacts are local and can be mitigated.

Additionally, negative impacts from human induced seismicity associated with CCS can occur if sites do not properly manage pressure. Similar to leak impacts, potential seismicity impacts are local and can be mitigated.

CCS Program Staff Activities and Milestones

Staff held a kickoff workshop on CCS in February 2016. This workshop included presentations by ARB staff, the California Energy Commission, U.S. Department of Energy, and a number of Non-Governmental Organizations (NGO). In order to build ARB staff expertise in CCS, and to provide an open forum for stakeholder discussion, staff further hosted a series of technical discussions with presenters from federal and state government agencies, NGOs, industry, and academia. Since February 2016 staff has hosted six technical discussions where experts in their respective fields presented on the following topics:

- Accounting Protocols;
- Well Mechanical Integrity;
- Monitoring;
- CO_2 Enhanced Oil Recovery;
- Site Selection; and
- Health and Environmental Risks, and Environmental Justice.

Staff have also engaged stakeholders in a number of one-on-one meetings, and has essentially opened a line of communication with interested stakeholders. As part of outreach activities and to gain knowledge, staff toured the following facilities:

- The CCS facility at the ADM ethanol plant in Decatur, Illinois;
- The PG&E McDonald island underground natural gas storage facility in Stockton, CA;
- The PG&E natural gas power generating facility in Colusa County, CA;
- The Pacific Ethanol production facility in Stockton, CA;
- The Shell Refinery in Martinez, CA.

In addition to our outreach efforts, staff conducted literature reviews on a number of subjects pertinent to CCS. These literature reviews involved comprehensive searches, review and analysis of the scientific literature, government documents, and other documentation available on each topic, and are covered in greater depth in the following sections.

Technical Discussions and Literature Reviews

Quantification Methodology /Protocol

Background

CCS accounting protocols provide methods (e.g., equations and procedures) to quantify CO_2 emission reductions associated with capturing, processing, transporting, and permanently sequestering anthropogenic CO_2 in geologic formations. Accounting protocols are one of several major components of the comprehensive CCS program being developed by ARB that will ensure emission reductions are real, permanent, quantifiable, verifiable, and enforceable.

Summary of the technical discussion

On April 5, 2016, ARB hosted a CCS accounting protocol technical discussion to glean insights into the merits and limitations of existing CCS accounting protocols, and to identify the specific components of existing accounting protocols that would be potentially suitable for the Cap-and-Trade and LCFS programs. Sixty seven people from academia, government agencies, industry, and NGOs participated in the discussion. Six presentations and two comment letters were provided by stakeholders. Below is the list of affiliations of presenters and the focus of each presentation:

- Alberta Environment and Parks, Offset quantification protocol for CO_2 capture and permanent storage in deep saline aquifers;

- Shell Oil, Shell's experience, observation, and perspectives on various aspects of a CCS project such as the environmental impact and risk assessment;
- Occidental Petroleum, Industrial experience and perspectives on CCS;
- National Energy Technology Laboratory (NETL), Perspectives based on the life cycle analysis approach for CCS;
- Lawrence Livermore National Laboratory (LLNL), Issues of accounting the emission reduction for CCS in California climate programs;
- Kruger Strategies, An overview of the USEPA accounting framework for CCS.

Key comments and concerns expressed by the stakeholders during the accounting protocol technical discussion are summarized below:

- Need to clearly define leakage, e.g., in Alberta movement of CO_2 plume outside of detection area and tenure lease is considered the same as CO_2 emissions to the atmosphere; in some other places leakage is defined only as CO_2 emitted directly to the atmosphere.
- Need to be clear about the system boundaries and what is to be "accounted" for.
- When using a life-cycle approach, displacement needs to be carefully considered. The displacement issue may significantly affect the accounting of CO_2 emission reduction. For example, what source of electrical generation is being displaced, the "average" generator, or the marginal generator?
- Stakeholders suggest reversals, permanence, and long term liability issues should be addressed in ARB's CCS QM or policies.

Summary of the staff literature review

The objective of this review was to conduct a comprehensive and thorough examination of existing CCS accounting protocols. Great effort has been made to ensure that ARB is up-to-date on the best available knowledge and best practices for each of the main elements of the existing protocols. Specific tasks of the literature review included identifying the main elements of each protocol, comparing the description and handling of each element in different protocols, and understanding the rationales of the differences in those protocols. Nine existing accounting protocols were studied and compared. The accounting protocols included in this review are listed below[11]:

- US EPA 40 CFR 98—Mandatory Greenhouse Gas Reporting, Subpart RR — Geologic Sequestration of Carbon Dioxide;
- Methodology for Greenhouse Gas Emission Reductions from Carbon Capture and Storage Projects, American Carbon Registry (ACR) 2015;
- ISO 14064-2:2006, Greenhouse gases - Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements;
- DIRECTIVE 2009/31/EC of the European Parliament and of the Council of 23 April 2009, on the geological storage of carbon dioxide;
- 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories: Volumes 1 and 2;

---

[11] Details of all nine standards/protocols can be found at ARB CCS website: http://www.arb.ca.gov/cc/ccs/meetings/meetings.htm.

- United Nations Framework Convention on Climate Change (UNFCCC), Decision 10/CMP.7, Modalities and procedures for carbon dioxide capture and storage in geological formations as clean development mechanism project activities, 2012;
- Canadian Standards Association and CSA America, Inc., Geological storage of carbon dioxide, Z741-12, 2012**;**
- Alberta Government, Quantification Protocol for CO2 Capture and Permanent Storage in Deep Saline Aquifers, 2015;
- A Greenhouse Gas Accounting Framework for Carbon Capture and Storage Projects, Center for Climate and Energy Solutions (C2ES), 2012**.**

These accounting protocols cover CCS-related work in the U.S., Canada, European Union, and a few international organizations. Four out of the nine protocols reviewed provide calculation procedures and equations for quantifying CO_2 reductions from CCS projects; the remaining five provide general guidelines and requirements for CCS projects but do not provide equations for calculating CO_2 reductions. The four protocols that provide calculation procedures for CO_2 reductions for CCS projects are: US EPA 40 CFR 98 Subpart RR; C2ES (2012); ACR (2015); and Alberta Protocol (2015). The calculation procedures of these four protocols were analyzed in greater detail by staff.

Existing accounting protocols provide useful information on general guidelines and requirements for various aspects of CCS projects. Some protocols such as US EPA 40 CFR 98 Subpart RR and ACR (2015) contain quantifying elements for CCS projects that can be incorporated into ARB's CCS QM. However, no single existing protocol can fully meet the specific needs of the Cap-and-Trade and LCFS programs. Staff will need to further evaluate the specific needs of these programs and develop a comprehensive QM and Permanence Protocol on the basis of these needs and the lessons learned.

Site Selection

Background

Site selection has significant impacts on the risk and success of CCS projects. A well-chosen site with reliable sealing layers, appropriate geology, and good spatial location could significantly decrease risks and challenges associated with a CCS project. Careful site selection can minimize the likelihood of atmospheric CO_2 leaks, and CO_2 subsurface migration out of intended storage volume, and maximize CO_2 trapping in the target storage zone. This makes site selection of paramount importance to CCS projects.

Summary of the Technical Discussion

On September 26, 2016, ARB hosted a CCS site selection technical discussion to seek input on the site selection process and criteria that are important to ensure permanent and safe CO_2 sequestration. Four presentations were given. The list of the organizations of presenters and the topic of each presentation is provided below:

- Shell Oil, site selection during the Quest project;
- Lawrence Berkeley National Laboratory, important site selection traits;

- University of North Dakota Energy and Environmental Research Center, site selection criteria and factors;
- Electric Power Research Institute, site selection during the Citronelle project.

Key comments and concerns expressed by the stakeholders during the technical discussion include:

- Careful selection of a good quality site is essential to CCS projects as it is difficult to engineer a way out of a bad site.
- Site selection requires an iterative process for data and risk evaluation.
- Every site has its unique characteristics, and may make prescriptive regulatory elements difficult to implement.
- As with any project, risks cannot be entirely eliminated in CCS projects; an ALARP approach (getting risks to As Low As Reasonably Possible) is essential.
- Key elements to consider during site selection include, but are not limited to, presence of other wells, presence and type of containment, injectivity, site capacity, potential transport costs, and anticipated monitoring requirements.
- In project areas where induced seismicity may be a concern, brine extraction may become an essential part of projects to ensure safe and permanent storage of CO_2 by reducing pressure build-up in the reservoir. In cases where brine extraction may become important, salinity of the brine and how the brine is disposed of will be key site selection factors.
- A single thick cap rock may be difficult to find in California; therefore, it may be better to allow storage complexes that contain many different thinner seals.
- A specific depth requirement for CO_2 storage in a supercritical state may be inappropriate. The 800 meter depth quoted in many papers is based on assumptions that do not apply in all cases. A requirement that CO_2 will remain supercritical based on pressure and temperature measurements may be more appropriate than a specific depth threshold.
- It may be useful to give preference to reservoirs with a dissipation interval above and/or below the reservoir. A dissipation interval is another reservoir with appropriate hydrologic characteristics such that if CO_2 begins to travel through a leak pathway toward the interval, the interval will allow pressure bleed off and provide an additional storage catch for CO_2.
- Characteristics of a reliable model will include: 1) the effect of the physical boundaries of a reservoir; 2) anticipated plume extent, pressure front extent, and area of review (AOR) boundaries; and 3) incorporation of seismic concerns. Static models may be fine for initial site selection and other early phases of a project, but dynamic models are necessary as a project evolves.

Summary of the Staff Literature Review

The objective of this literature review was to identify key traits that are essential to selecting a quality site for CCS and provide background on methods for evaluating those traits. In order to accomplish this, staff reviewed six major best practices manuals[12,13,14,15,16,17] as well as scientific literature[18] that cover important traits and site selection methods.

Based on the literature review, staff found that the following factors should be evaluated when considering a site for CCS. Not all of these factors will necessarily appear in ARB's CCS QM or Permanence Protocol; instead, this list includes nearly all the factors identified in the literature for optimal CCS site selection.

- Geologic and Containment Factors
  - Storage formation characteristics: depth, porosity, permeability, thickness, maximum capacity, fracture pressure, level of heterogeneity (vertical and horizontal), temperature.
  - Confining formation characteristics: porosity, permeability, thickness, continuity and integrity, fracture pressure, level of heterogeneity (vertical and horizontal).
  - Trapping mechanisms and potential leakage pathways of CO_2.
  - Potential injectivity: including planned injection rate and total injection volume.
  - Geochemical interactions.
  - Geomechanical response to anticipated pressures.
  - Hydrological response and communication in reservoir.
  - Existing and anticipated seismic concerns.
  - Pre-injection backgrounds for characteristics such as groundwater chemistry, seismic levels, pressure/temperature conditions, etc.
- Modeling Factors and Plume Size
  - Modeling parameters, data needs, and the costs of collecting data.
  - Limitations or uncertainties that exist in the model.
  - How reservoir boundaries will affect the plume and the anticipated plume extent.
  - Areas of seismic concern from a modeling perspective.
- Regulatory Requirements
  - Applicable regulations that may impact the project.
  - Regulatory agencies that should be involved in the project.
  - Well classification and permitting standards under current regulations.
  - The need and amount of corrective actions for the site.
  - The long-term liability associated with the project.
- Site Development/Local Factors

---

[12] National Energy Technology Laboratory, U.S. Department of Energy: Best Practices for Site Screening, Site Selection, and Initial Characterization for Storage of CO_2 in Deep Geologic Formations, June 2010.
[13] World Resources Institute, Guidelines for Carbon Dioxide Capture, Transport, and Storage, 2008.
[14] Cooperative Research Centre for Greenhouse Gas Technologies, Storage Capacity Estimation, Site Selection and Characterisation for CO2 Storage Projects, 2008.
[15] International Energy Agency Greenhouse Gas R&D Programme and Alberta Research Council, CCS Site Characterisation Criteria, July 2009.
[16] Det Norske Veritas AS, Geologic Storage of Carbon Dioxide, July 2013.
[17] California Energy Commission, Health, Safety, and Environmental Screening and Ranking Framework for Geologic CO2 Storage Site Selection, 2006.
[18] Stefan Bachu, Screening and Ranking Sedimentary Basins for Sequestration of CO2 in Geological Media in Response to Climate Change, 2003.

  - Proximity to sources of CO_2, protected and sensitive areas, and population centers.
  - Existing resource development and potential use of nearby infrastructure.
  - The size of anticipated Area of Review.
  - Pore space ownership, and surface and subsurface access issues.
  - Right-of-ways and competition for right-of-ways.
  - Community concerns and feedback.
- Economic Factors
  - The economic feasibility of a site development based on the above considerations and a preliminary site development plan.

Because of the interactions between geologic formation traits, many of these site selection factors would be more amendable to performance based standards rather than prescriptive standards, and would require an evaluation on a site per site basis. One approach that staff has discussed regarding site selection is to provide a "checklist" of prescriptive requirements, as well as a suite of more flexible performance requirements. This or a similar approach could allow a streamlined analysis for relatively straightforward projects, while granting flexibility for "non-standard" projects.

Well Integrity

Background

Well integrity is important to ensure that CO_2 injected into storage reservoirs will not migrate into unintended strata, leak to the atmosphere, or compromise human health, the environment, or resources in the local area. Depending on the well density of the site, the CO_2 plume from a CCS injection well could impact tens to hundreds of wells[19]. Each of these impacted wells will need to be analyzed for well integrity to ensure that containment of the CO_2 is maintained. Adequate well integrity is a fundamental factor in ensuring that any benefits a project receives for sequestering CO_2 are based on permanent CO_2 sequestration.

Summary of the Technical Discussion

On May 12, 2016, ARB hosted the CCS well mechanical integrity technical discussion to analyze the impact well mechanical integrity may have on CCS projects. Below is the list of affiliations of presenters and the focus of each presentation:

- University of South Dakota, risk and criteria for legacy wells and tools for well integrity;
- Battelle Institute, well design, failure, and cement concerns;
- Los Alamos National Laboratory, cement degradation;
- Elk Petroleum, construction standards and their effectiveness;
- University of Cincinnati and GDF Services, abandoned well emission study;
- Natural Resources Defense Council, UIC/Class II well integrity and the difference between EOR and Saline well integrity concerns;

---

[19] Gasda, Sarah E., Stefan Bachu, and Michael A. Celia. "Spatial characterization of the location of potentially leaky wells penetrating a deep saline aquifer in a mature sedimentary basin." Environmental Geology 46 (2004). Pages 707-720.

- Global CCS Institute, EOR legacy well concerns and the Weyburn project;
- University of Texas at Austin, groundwater and soil impacts above CO2 injection fields.

Key comments and concerns expressed by the stakeholders during the well integrity technical discussion are summarized below:

- Well mechanical integrity is an important factor to be considered when evaluating CCS sites because pre-existing (legacy) wells are the primary concern as leakage pathways.
- Evaluating legacy wells can be very time intensive and complex, and the conclusions will rely as much on the availability and completeness of historic logs as on the qualities of the wells. The quality of a well's original construction plays a very large part in the quality of the well's integrity over time.
- In most cases cement will exhibit a self-healing type behavior due to chemical reactions that counteract the the dissolution and help maintain well integrity.
- In contrast, traditional carbon steel casing can deteriorate very quickly if exposed to CO_2 and water; however, careful cement jobs and correctly applied corrosion resistant materials can be used to protect the metals and appear to be adequate prevention of casing corrosion.
- A study of methane leak rates from active and abandoned wells was presented and discussed. Based on the study and discussion, plugging wells is an effective method of maintaining well mechanical integrity, and the majority of plugged wells do not have leak pathways. Of the 138 wells evaluated (20 unplugged, and 118 plugged) only 1 plugged well was a positive source of methane while 8 of the 20 unplugged wells were positive sources of methane.
- Significant leaks that do occur tend to be the result of a handful of "super-emitters" that will need to be identified and, if found, be carefully remediated and thoroughly monitored at CCS sites to ensure such wells do not pose a significant risk to the permanence of CO_2 sequestration.

Summary of the Staff Literature Review

The objective of this review was to evaluate the leakage concerns associated with well integrity from CCS projects. ARB staff reviewed 18 documents that included information on well material degradation analysis, evaluations of regional well leak rates, and existing well integrity standards and recommendations. The well integrity review covers three areas.

First, staff researched material degradation studies that examined the chemical interaction of CO_2 with well materials under various subsurface conditions. **Figure** 1 shows a simplified diagram of a typical well's interior structure and a list of the possible leakage pathways that can form inside a well. These leakage pathways can form from weakness in original well construction and/or degradation of the cement and casing metal due to the chemical interaction with CO_2 and water[20]. High risk wells such as

---

[20] Bachu, Stefan, and Michael A. Celia. "Assessing the Potential for CO2 Leakage, Particularly Through Wells, From Geological Storage Sites." Geophysical Monograph Series 183. Copyright 2009 by the American Geophysical Union. Pages 203-215.

older, poorly constructed wells, or wells already identified to have well integrity concerns should be avoided; if the use of a high risk well is unavoidable, increased monitoring is essential. In many cases, reactions between cement and CO2-rich brines will result in the precipitation of mineral deposits within cement fractures, which lowers the risk of leakage from legacy wells because these mineral precipitates promote self-sealing and closure of leakage pathways [21]. Only large, high flow, leakage pathways are likely to suffer further degradation that increases cement permeability and decreases well integrity. For well casings, steel corrosion rates are much too high to allow CO_2-rich brines direct contact with the metal casing; however, an appropriately situated cement sheath between the metal casing and the brine can protect the steel casing from corrosion[22]. When possible, cement bond logs, casing corrosion analysis, and other well testing techniques should be used to validate the quality of the original well construction and its current mechanical integrity.

Second, staff evaluated well studies that reviewed emissions from many wells, to assess how common it is for legacy wells in a given region to develop a leak to the surface. It appears that the majority of well leak emissions come from a few super-emitters and that the majority of wells do not have significant mechanical integrity problems[23]. Determining the presence and/or risk of such wells in a CCS project area will be vital to ensuring permanence of CO_2 sequestration. Tubing and annulus pressure and wellbore temperatures should be regularly monitored as a failsafe and warning system against well integrity failure whenever possible[24].

Third, staff reviewed existing well standards that include sections for the maintenance of well integrity. This review included the U.S. Environmental Protection Agency (U.S. EPA) Class II and Class VI underground injection control permitting standards, the Division of Oil, Gas, and Geothermal Resources (DOGGR) well permitting standards, the NORSOK (Norwegian petroleum industry) well standards, the American Petroleum Institute guidance standards, and suggested Society of Petroleum Engineers well standards.

Based on the review, well integrity is an essential consideration when evaluating CCS projects, and well integrity in legacy wells is a particularly important aspect. In the majority of cases minor leaks will not instigate well degradation but instead promote self-sealing behavior. Well leaks are relatively rare, and the majority of well leak emissions are from a small number of large leaks that, with sufficient monitoring and maintenance, could be quickly identified. Once identified, appropriate corrective action

---

[21] Carroll, Susan, et al. "Review: Role of chemistry, mechanics, and transport on well integrity in CO2 storage environments." International Journal of Greenhouse Gas Control 49 (2016). Pages 149-160.

[22] Choi, Yoon Seok, Daivd Young, Srdjan Nesic, and Linda G.S. Gray. "Wellbore integrity and corrosion of carbon steel in CO2 geologic storage environments: A literature review." International Journal of Greenhouse Gas Control 16S (2013). Pages S70-S77.

[23] Kang, Mary. "Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania." Proceedings of the National Academy of Sciences of the United States of America, Volume 111, No. 51. December 2014. Pages 18173-18177.

[24] Syed, Talibuddin, and Thor Cutler. "Well Integrity Technical and Regulatory Considerations for CO2 Injection Wells." Paper prepared for presentation at SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production. April 12-14, 2010.

can be taken to stop the leak and to instigate other mitigation measures to offset the release or other damages that may have occurred.

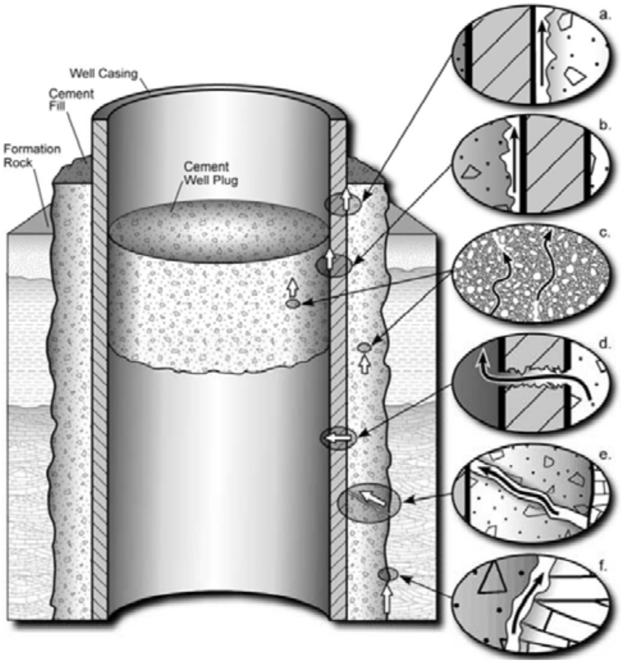

Figure 1: Schematic of possible leakage pathways along a well (a) between cement and outside of casing, (b) between cement and inside of casing, (c) through cement, (d) through casing, (e) in cement fractures, (f) between cement and rock.[25]

Monitoring

Background

Monitoring, Reporting, and Verification (MRV) is used to ensure that CO_2 injected into storage reservoirs is permanently contained within the geologic formations, moving as expected in the subsurface, and that any unexpected CO_2 plume migration or leaks to the atmosphere are detected early so that appropriate responses can be taken. Monitoring is done with various technologies that can detect and quantify leaks. A typical monitoring plan will provide information for estimating the amount of CO_2 stored at a storage site, monitor the site for plume migration, leaks, or deterioration of storage reservoirs over time, and allow us to determine whether the CO_2 is permanently sequestered and does not harm the environment. Well-designed monitoring plans are reactive to any changes detected during injection, and a verification component assessing the amount and location of stored CO_2 is usually included.

Summary of the monitoring technical discussion

On August 5, 2016, ARB hosted the CCS monitoring technical discussion to gather information on monitoring for CCS projects. Three general topics were covered:

---

[25] Celia, Michael A., et al. "Modeling Critical Leakage Pathways in a Risk Assessment Framework: Representation of Abandoned Wells." In the Conference Proceedings from the Fourth Annual Conference on Carbon Capture and Sequestration DOE/NETL. May 2-5, 2005.

monitoring plan components, monitoring tools and techniques, and leak detection and quantification. More than 60 people attended the discussion both in person and via webinar, and 7 stakeholders gave presentations. Below is a list of presenter affiliations and topic areas:

- Shell Oil, Shell Quest project monitoring;
- Natural Resources Defense Council, General overview of monitoring;
- Wade, LLC, Development of monitoring plans;
- Berexco and Trenton Agri Products, CO2-EOR project monitoring;
- LICOR Biosciences, Surface monitoring technologies;
- University of Texas at Austin, Deep subsurface monitoring;
- University of Texas at Austin, Environmental monitoring.

The following are key comments and concerns expressed by the stakeholders during the technical discussion:

- Monitoring plans are site specific. Certain technologies would not be useful or relevant depending on the storage site. A monitoring plan for a CO2-EOR project will differ substantially from a plan for a saline storage project.
- Monitoring plans should not be static, and should be reevaluated during the lifetime of the project and modified depending on the data and what is observed.
- Contingency plans should be in place for situations where leaks are detected or where evidence can be shown on the unexpected migration of the CO_2 plume.
- Monitoring technologies can vary greatly in cost. Some technologies are not practical or are prohibitively expensive for projects that are smaller or not well-financed. Considering cost-effectiveness is important for developing a monitoring plan.
- Atmospheric monitoring is likely not capable of early detection of leaks, but is useful to reassure the public for health and environmental purposes. Subsurface monitoring is useful for leak prevention and detection and monitoring plume migration. System-wide surface monitoring would not be cost effective and is not recommended. Targeted surface monitoring, subsurface monitoring, and tracking of CO_2 plume are recommended.
- Monitoring plans should be risk-based. Risk assessment is critical to site selection, and different sites will have a different set of risks.
- Monitoring plans should be adaptive and flexible in order to encourage improvements in monitoring techniques, and should not stifle innovation by including or excluding specific technologies.
- New monitoring techniques may eliminate the need to establish baselines.
- Monitoring plans should include strategies for detecting and quantifying leaks.

Summary of the monitoring literature review

Staff examined various tools and techniques used to monitor CCS storage sites. Monitoring technologies can generally be broken down into 3 categories based on spatial location: atmospheric, near-surface, and subsurface monitoring. **Table 1** shows most of the technologies that are currently available based on this categorization. Monitoring tools can also be categorized by their readiness for commercial field use, and have been described as either in the development, demonstration, or commercial stage. The costs and benefits of many of the tools and techniques were also examined. The literature shows which technologies are generally more or less cost-effective and more or less costly, but there are no significant quantitative data available that demonstrate these findings.[26,27]

Based on the review, existing methods are able to detect near surface leaks above background CO_2 flux, but are not able to quantify the leaks with adequate accuracy; nevertheless, advances in technologies have the potential to better quantify the leaks. To date detecting small-scale leaks over large areas is still technically challenging.[28] For leak detection, subsurface monitoring techniques are more useful because they can track plume migration. Due to the high variability of background CO_2 levels and difficulty in establishing a baseline it may not be appropriate to rely on near-surface or atmospheric monitoring for leak detection. In addition, it takes time for leaked CO_2 to reach atmosphere, and near-surface monitoring may result in late detection. Surface (or atmospheric) monitoring can assure the public that the health, safety, and environment are protected from any CO_2 leaks, and is important for CCS projects. The literature shows that monitoring plans should be flexible and would change depending on conditions at the storage site, changes in technologies, and the different monitoring phases of a CCS project. Monitoring plans should also include a contingency plan that is reactive to any unexpected changes in conditions at the storage site.[29]

---

[26] National Energy Technology Laboratory, U.S. Department of Energy, Best Practices for Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations – 2012 Update. 2_{nd} Edition.

[27] Plasynski, Sean I., et al. "The critical role of monitoring, verification, and accounting for geologic carbon dioxide storage projects." Environmental Geosciences, v18, no.1. 2011.

[28] Andrew J. Feitz et al., "An assessment of near surface CO leakage detection techniques under Australian conditions," Energy Procedia, 63 (2014) 3891 – 3906.

[29] National Energy Technology Laboratory, 2012.

Table 1: Monitoring technologies

Atmospheric Monitoring	
Optical Sensors	Cavity ring-down spectroscopy (CDRS) Non-dispersive infrared spectroscopy (NIDR) Differential adsorption lidar (DIAL) Light detection and ranging (LIDAR)
Atmospheric Tracers	Passive tracer sampling (e.g. flask, sorbent) Multi-tube remote samplers Wind-vane samplers
Eddy Covariance	Eddy covariance (EC) flux towers
Surface and Near-Surface Monitoring	
Soil and Vadose Zone Monitoring	Flux accumulation chambers Soil-gas tracer sampling Soil-carbon analysis High-resolution infrared (IR) gas analyzer Soil-CO_2 fiber-optic sensors
Shallow Groundwater Monitoring	Shallow groundwater sampling Geochemical analyses (e.g. pH, alkalinity, dissolved cations) Isotopic carbon analyzers Geochemical tracer studies (e.g. stable/radioactive isotopes)
Surface Displacement Monitoring	Tiltmeter array analysis Synthetic aperture radar interferometry (InSAR) Permanent scatterer InSAR (PSInSAR) Global Positioning Systems (GPS)
Ecosystem Stress Monitoring	Hyperspectral imaging Multi-spectral imaging
Subsurface Monitoring	
Well Logging Tools	Density Neutron porosity logs Pulsed neutron tools (PNTs) Acoustic logging Dual-induction logging
Downhole Monitoring Tools	Downhole/wellhead pressure Temperature, pH, alkalinity, and oxygen-activation gauges Sonic logging (e.g. corrosion monitoring) Flow meters Thermal perturbation sensor (DTPS)
Seismic Methods	Surface seismic (3-D, 2-D) Borehole/cross-well seismic (e.g. vertical seismic profile [VSP]) Passive (micro) seismic Fiber-optic geophone technology for borehole seismic
Subsurface Fluid Sampling	Wireline-based samplers U-tube samplers Gas membrane sensor systems Geochemical tracer studies (e.g. stable/radioactive isotopes)
Gravity	Borehole and surface gravity measurements
Electrical	Cross-well electrical resistivity tomography (ERT) Surface-downhole ERT Controlled-source electromagnetic (CSEM) surveys

CO_2 Enhanced Oil Recovery

Background

CO_2 enhanced oil recovery (CO2-EOR) is a tertiary method of crude oil production in which supercritical CO_2 is injected into oil reservoirs to recover additional crude oil. In doing so, the injected CO_2 can remain sequestered in oil reservoirs. CO_2-EOR offers GHG emissions mitigation and an opportunity to gain more experience on geological carbon sequestration and allow the knowledge and infrastructure to be developed for dedicated geological carbon sequestration projects such as sequestration in saline formations.

CO2-EOR projects exist in order to extract oil, and generally do not place a particular focus on permanent storage of CO_2. In fact, in order to minimize CO_2 costs, CO2-EOR operators may retrieve CO_2 from exhausted sites and transport that CO_2 for re-use in other sites. Some CO_2 is retained within injection sites and remains un-retrievable (sometimes called incidental sequestration). As a result, all CO2-EOR projects may achieve some level of CO_2 sequestration. Where CO2-EOR projects may differ from one another is the source of the CO_2 (natural[30] vs. anthropogenic), the amount of CO_2 injected that is sequestered, and the permanence of the sequestration.

Summary of the Technical Discussion

On August 23, 2016, ARB hosted the CO2-EOR technical discussion to gather inputs related to CO2-EOR. Below is the list of affiliations of speakers and the focus of each presentation:

- Clean Air Task Force, GHG quantification and CO2-EOR for CO_2 storage;
- Advanced Resources International, Inc.: Mechanical integrity, CO_2 storage in residual zones, and CO_2 injection methods;
- University of Wyoming: CO2-EOR injection and production wells;
- Natural Resources Defense Council: CO2-EOR challenges and opportunities;
- Conestoga Energy Partners: CO_2 capture from ethanol plant and injection;
- Sean McCoy: Lawrence Livermore National Laboratory: Co-optimization and CO2-EOR LCA review;
- Berexco and Trenton Agri Products: Industry experience with CO2-EOR.

The following are key comments and concerns expressed by the stakeholders during the technical discussion:

- Reservoir pressure monitoring, particularly sustained casing pressure monitoring, is important for CO2-EOR.
- EOR fields tend to be well characterized, and therefore MRV plan development will be different and may be easier relative to dedicated saline storage.
- Potential movements of CO_2 outside of the project boundary need to be considered in the QM.

---

[30] CO_2 from natural geologic sources, such as natural CO_2 domes, that would not otherwise be released would not qualify for CCS benefits under California's climate programs.

- Legacy CO2-EOR wells present a risk of CO_2 leakage, although the failure rates may be small.
- Use of "next generation" CO_2-EOR will expand oil production and CO_2 storage capacity in the U.S. For example, residual oil zones (ROZs), which lie below existing main pay zones and beyond and have similar geologic characteristics, offer opportunities for additional CO_2 storage. In addition to "next generation" CO2-EOR, there are alternative approaches to increase CO_2 storage including (1) injecting CO_2 longer (2) continuously injecting CO_2 instead of alternating with water (3) injecting CO_2 into other geologic horizons (e.g. saline formations) accessible from same surface infrastructure used for CO_2-EOR and (4) producing residual water to make room for more CO_2 storage.
- One stakeholder argued that switching to well-designed and leakage free CO_2-EOR projects results in system-wide GHG reductions irrespective of system boundary considerations and whether emissions from combustion of CO2-EOR-derived fuels are additional; however the magnitude of reductions varies depending on these assumptions.
- Most states have primacy on Class II wells, and there are variations on stringency and completeness of class II rules. Class II well operators have discretion over CO2-EOR operations. Some industry participants argue that class II well requirements are adequate for EOR CCS, and that the stringency of MRV can be varied based on the size of EOR projects since leakage from larger projects may likely be higher.
- Materials near perforations are most susceptible to corrosion which may increase leakage risks. Use of corrosion resistant materials is recommended in such zones.
- Companies may vent CO_2 at the beginning of CO2-EOR operations until they have enough CO_2 to make recycling economical. Therefore, venting CO_2 will need to be considered in the QM.

<u>Summary of the Staff Literature Review</u>

Globally, CO_2 storage potential in traditional oil reservoirs is estimated to be 370 billion metric tons; furthermore, the USA alone has the potential to store 51 billion metric tons of CO_2 in CO2-EOR projects[31]. Beyond traditional oil reservoirs, there is a potential to sequester CO_2 in residual oil zones and unconventional reservoirs such as tight oil formations, and research interest is growing in this emerging area.

The reservoir characteristics used to identify suitable reservoirs for CO_2 injection are well established. Important selection criteria include reservoir depth, pressure, temperature, permeability, oil gravity, viscosity and residual oil saturation. CO_2 can be injected into a reservoir in a variety of ways: continuous CO_2 injection, CO_2 huff-n-puff[32],

---

[31] Godec, Michael L., Vello A. Kuuskraa, and Phil Dipietro. "Opportunities for using anthropogenic CO_2 for enhanced oil recovery and CO_2 storage." Energy & Fuels 27.8 (2013): 4183-4189

[32] Here, CO_2 is injected for a certain period of time while keeping the production wells closed. After injection, the injection wells are shut in to allow CO2 to have adequate contact with crude oil to become miscible

and Water-alternating–gas (WAG). Of these the WAG method has become a preferred method as it helps store more CO_2 while recovering more crude oil.

Staff found three important considerations for the CCS program in order to incentivize higher CO_2 storage and minimize CO_2 leakage risks.

- *Co-optimization of CO_2 storage and crude oil recovery*: With increasing regulatory emphasis on GHG reductions and carbon pricing, co-optimizing both crude oil production and CO_2 storage may become an attractive choice. The well control process, which controls the closing and opening of injection wells and production wells has been found to store more CO_2 while maximizing the crude oil recovery. Also the distance between the injection and production wells and the timing of alternating CO_2 and water injection, also known as the WAG ratio, were identified as critical parameters affecting CO_2 storage and oil recovery. In addition to modes of operation, reservoir characteristics such as reservoir permeability, porosity, and thickness can impact crude oil recovery and CO_2 storage.
- *Life cycle system boundary*: Research to date on life cycle analysis of CO2-EOR indicates that the system boundary consideration impacts the GHG reduction credits of CO2-EOR operations. The cradle-to-gate, gate-to-gate, gate-to-wheel and cradle-to-wheel LCAs have been performed which offer varying degrees of GHG savings. Hence, the system boundary is going to be an important consideration for the CCS QM. The same is true for all accounting frameworks of individual programs.
- *CO_2 Leakage*: With over 40 years of experience in operating CO2-EOR projects, significant subsurface leakage has rarely been reported[33]. However, there have been no CO_2 monitoring and tracking requirements, which may have contributed to the no-leakage reports. One should note that methane leakages have been observed in analogous reservoirs. In addition, none of the CO2-EOR projects have stopped operating and no information is available on post-closure status. There is a possibility that given the costs of CO_2 capture ($30-110/metric ton), EOR operators may prefer to decompress the stored CO_2 and move some or most of the CO_2 to other fields for injection if there is no economic benefit for the stored CO_2. To mitigate the risks of CO_2 surface leakage and intentional CO_2 transfer, the CCS program should be designed to account for such risks. Moreover, the monitoring plans should lay out the framework for detecting, managing, and mitigating CO_2 leaks if they occur.

Health and Environmental Risks, and Environmental Justice

Summary of the Technical Discussion

On September 27, 2016, ARB hosted a CCS health, environmental risks, and environmental justice technical discussion to seek input on potential health, environmental, and environmental justice concerns associated with CCS projects. Six presentations were given. A list of the organizations and the topic of their presentations is provided below:

---

[33] National Enhanced Oil Recovery Initiative, CO2-EOR Safety, http://www.neori.org/NEORI_CO2EOR_Safety.pdf

- Los Alamos National Laboratory, An overview of the potential impacts of CO_2 on shallow water aquifers;
- United States Geological Survey, Microseismicity monitoring at the Decatur, Illinois CO_2 sequestration demonstration site;
- Lawrence Livermore National Laboratory, Risk management and induced seismicity;
- Lawrence Berkeley National Laboratory, Optimization of fluid injection and extraction for reservoir management and risk mitigation during CO_2 sequestration;
- AB 32 Environmental Justice Advisory Committee, CCS implications for environmental justice;
- Geoscience Australia, Soil and atmosphere.

Key comments and concerns expressed by the stakeholders during the technical discussion include:

- There is substantial scientific evidence that with careful site selection and operation, the likelihood of leaks reaching aquifers, topsoil, or air is very low.
- CO_2 released into aquifers is not dangerous by itself; however, depending on the volume and the hydrochemical conditions it may lead to increase in metal concentrations. This does not occur in all cases, and scientific literature suggests it rarely causes the concentrations to rise above current drinking water standards.
- U.S. EPA established a permitting process under the Underground Injection Control program to protect underground drinking water sources from CCS. Equivalent requirements should be established as minimum requirements for areas outside U.S. EPA jurisdiction.
- If CO_2 leaks to the topsoil it can lead to localized patches of plant stress or death. Limited impact may occur if the soil gas reaches CO_2 concentrations of 5-40%, and detrimental impacts may occur if soil gas reaches CO_2 concentrations of >40%. Soil gas can recover within weeks to months after the leak is stopped.
- CO_2 is heavier than air, but unless it is able to accumulate, it tends to disperse quickly (seconds to minutes), and presents little threat to human or animal health.
- Injection projects that produce significant induced seismicity are rare when considering the number of injection projects that occur. While there is a small risk of induced seismicity, it is case dependent, and the vast majority of injection projects do not produce concerning seismic events. However, this is a concern that should be carefully considered in site selection.
- Seismicity risk is site specific and will change as the plume and pressure front expand; therefore, seismic evaluation will need to be an iterative process that continues throughout the project's lifetime.
- Pressure management may be an effective method for reducing induced seismicity and containment risks.
- The concerns from an environmental justice perspective include:
    - There must be a public process for all aspects of CCS projects.
    - Local air quality impacts from CCS projects.

  - Leaving biomass residues in place to decompose naturally rather than using biomass in combustion and CCS plants.
  - The potential for increases in oil production associated with CO2-EOR.
  - Analysis of lifecycle impacts of CCS projects on future generations.

Summary of Staff Literature Review

The objective of this review was to better understand the environmental effects of CCS projects. This review was split into three areas of impact: water, air and soil, and induced seismicity. There is a lack of data on the potential environmental impacts of CO_2 leakage from actual CCS projects, since CO_2 leakage of an appreciable degree have not been observed to date. Lab experiments, controlled field injection tests and modelling, and controlled CO_2 release studies have been the common methods to evaluate the possible environmental impacts of CO_2 leaks. These efforts are further complemented by analogue studies of CO_2 leaks from natural systems such as the migration of geologically produced CO_2 and brine into near-surface aquifers or release of CO_2 from volcanic activities.

Potential Impact on Water Resources

CO_2 released into an aquifer or the sea floor can create anaerobic conditions, increase acidity (i.e., decrease pH) and alter in-situ chemical reactions resulting in mobilization of metals (e.g. Al, Fe, Zn, Co, Pb, and Cu). In addition, the displacement of reservoir brines to an overlaying aquifer or the sea floor may occur. Since brines contain high concentrations of dissolved substances and elevated levels of toxic trace elements (e.g., As, Pb, and U), they can alter the chemistry of water resources.

The effects of increases in acidity, anaerobic conditions and metal mobilization may manifest in lower metabolic activities, growth, and reproduction of micro and macro-organisms in groundwater and benthic communities on the sea floor.[34] [35] The magnitude of impact will depend not only on the amount of CO_2 leakage but also on the site specific characteristics such as hydrodynamics (e.g., ground water flow and tidal waves) and rock compositions. For example, if groundwater flow is higher, it can dilute the impact of CO_2. While living organisms can recover quickly from a moderate increase in acidity due to a small-scale and short-term CO_2 leakage, an exposure to a severe acidity increase from a large-scale and /or long-term CO_2 leakage may cause deaths of organisms.[36]

The impact of CO_2 leakage is minimized if occurring in unconfined aquifers, which allows the CO_2 to migrate to the unsaturated zone and finally to the atmosphere thereby limiting the CO_2 in a vertical leakage path. If CO_2 leaks into confined aquifers, it can create a large and long-term CO_2 plume impacting the groundwater quality and

---

[34] Carroll, A. G., et al. "Environmental considerations for subseabed geological storage of CO_2: A review." Continental Shelf Research 83 (2014): 116-128.

[35] Pörtner, Hans O., Martina Langenbuch, and Anke Reipschläger. "Biological impact of elevated ocean CO_2 concentrations: lessons from animal physiology and earth history." Journal of Oceanography 60.4 (2004): 705-718.

[36] Jones, D. G., et al. "Developments since 2005 in understanding potential environmental impacts of CO_2 leakage from geological storage." International Journal of Greenhouse Gas Control 40 (2015): 350-377.

organisms. The buffering capacity provided by carbonate rich aquifers (calcite/dolomite) can provide additional protection to organisms from an increase in acidity. As acidity decreases down-gradient due to the buffering effect, hazardous metals are removed from water via adsorption, a process known as scavenging. Studies on natural CO_2 leaks show that contaminants of concerns have remained within drinking water limits.[37]

Overall, the impact on water quality and aquatic organisms from a small-scale (<1 t/day) and short-term (less than 40 days) CO_2 leakage may be limited due to buffering/scavenging effects as well as the resiliency of organisms to adapt. Large scale CO_2 leakage (>10 t/day) may be a concern; however, robust site selection criteria and monitoring and verification requirements can minimize this risk. Even if this low probability large–scale CO_2 leakage occurs, the impact is localized. The leakage can be quickly detected and actions can be taken to minimize/eliminate CO_2 leakage by plugging the leaking reservoirs.[38]

Potential Impact on Air and Soil

CO_2 is heavier than air. If CO_2 is able to accumulate in a below or near ground-level enclosure such as the basement of a building or a poorly ventilated enclosure, there is risk of CO_2 accumulation exceeding safe limit for human and animal health. In such cases, safety measures such as a CO_2 detection device should be in place.[39] Low concentration of CO_2, as naturally exists in air, does not harm human health and other biological life. The CO_2 concentration in air is very low at about 0.04%, compared to the 4% level considered as dangerous by NIOSH[40]. CO_2 mixes and disperses rapidly in air, and in most cases, potential leaks associated with CCS to air are not considered a health concern at above ground level in an open field.

Capture of CO_2 consumes energy. CCS will cause small increase in local criteria pollutant emissions if not regulated properly. However, since CCS is applicable to large stationary CO_2 sources, technologies for criteria pollutant emissions mitigation are available and can highly likely be applied cost-effectively.

The natural CO_2 concentration in soil varies with geographic locations and depths and can be 1-2 orders of magnitude higher than the CO_2 concentration in air[41]. Plant response to soil CO_2 concentration depends on plant species and begins when soil CO_2 concentration reaches 4%–8%. With highly elevated CO_2 concentration (e.g., >20%), significant effect on plants and microorganisms has been observed; and the ecosystem seems to adapt to different conditions resulting from elevated CO_2 concentration via

---

[37] Jones D. G, et al., 2015

[38] ibid

[39] U.S. Geological Survey, Invisible CO_2 Gas Killing Trees at Mammoth Mountain, California, U.S. Geological Survey Fact Sheet: 172-96
Online Version 2.0, https://pubs.usgs.gov/dds/dds-81/Intro/facts-sheet/GasKillingTrees.html

[40] U.S. Geological Survey, Carbon Sequestration to Mitigate Climate Change, U.S. Geological Survey Fact Sheet: 2008-3097

[41] Carbon Dioxide in Soil, Railsback's Some Fundamentals of Mineralogy and Geochemistry, University of Georgia Department of Geology, http://www.gly.uga.edu/railsback/FundamentalsIndex.html

species substitution and adaptation. A shift towards anaerobic and acidophilic species has been observed with elevated soil CO_2 concentration.[42,43]

Risk of Induced Seismicity

Induced seismicity is seismicity caused by human activities and is most commonly related to the injection or extraction of fluids into or out of the subsurface. To date, studies of CCS related induced seismicity are highly limited, and much of relevant, publicly available research has been derived from analogue studies of other types of fluid injection. These analogues include hydraulic fracturing, enhanced oil recovery, wastewater disposal, and geothermal wells. Staff looked into analyses of the history and theoretical causes of induced seismicity, analogues examples, and induced seismicity risks and risk mitigation techniques.

Based on statistical analysis the risk of an injection well inducing seismicity is low. There are approximately 35,000 active wastewater disposal wells, 80,000 active enhanced oil-recovery wells, and tens of thousands of wells hydraulically fractured each year in the United States but only a few dozen have ever been associated with induced seismicity that can be felt[44].

The two factors that are commonly believed to cause induced seismicity are: introducing changes to the pressure near a critically stressed fault, and injection of fluid into or near basement rock which may increase the seismic response. Of the four analogue examples, wastewater disposal wells are the most likely to induce seismicity. Given that CCS injection wells are somewhat similar to wastewater disposal wells, CCS projects should evaluate induced seismicity hazard and risk and take appropriate mitigation steps. Such steps may include appropriate risk assessment, data collection and monitoring, pressure management, modeling, magnitude threshold limits, and emergency response plans.

Technology and Economics

Background

CCS is suitable for use with large stationary sources of CO_2 due to the benefits of economies of scale and relatively high concentration of CO_2 compared to atmospheric concentrations. Sources that may be able to take advantage of CCS include coal and

---

[42] Lee H. Spangler, Laura M. Dobeck, Kevin S. Repasky, A shallow subsurface controlled release facility in Bozeman, Montana, USA, for testing near surface CO2 detection techniques and transport models, Environ Earth Sci, Special Issue, DOI 10.1007/s12665-009-0400-2

[43] Martin Krüger, Julia West, et al., Ecosystem effects of elevated CO_2 concentrations on microbial populations at a terrestrial CO_2 vent at Laacher See, Germany, Energy Procedia 1 (2009) 1933–1939

[44] Rubinstein, Justin L. and Alireza Babaie Mahani. "Myths and Facts on Wastewater Injection, Hydraulic Fracturing, Enhanced Oil Recovery, and Induced Seismicity." *Seismological Research Letters* 86, no. 4 (2015).

Additional ARB Note: we specify ‘felt’ induced seismicity because induced micro-seismicity (seismicity of such low magnitude it cannot be felt at the surface) occurs in all injection projects but has no negative impacts to the project or the surrounding region. Induced seismicity only becomes problematic when it reaches sufficient magnitudes.

natural gas power plants, ethanol plants, cement plants, refineries, and iron and steel plants. The high capital and operation and maintenance (O&M) costs of CCS projects and the lack of carbon market value of CCS activities are considered major barriers currently to the deployment of CCS as a GHG mitigation option. Incentives or carbon prices are considered necessary for wide deployment of CCS. Understanding of the cost and economics of CCS projects is essential to the analysis and discussion of CCS related policies. Staff did not host a technical discussion on technology and economics of CCS, but did conduct a literature review.

Summary of the staff literature review on capture technology

CO_2 capture is the primary cost component of a typical CCS project. Technology advances may significantly reduce the cost of CO_2 capture and thus the cost of CCS. Understanding the current status and future trends of CO_2 capture technology and cost is essential to CCS related policy making. There are a range of CO_2 capture technologies currently available including chemical solvent absorption, physical sorbent (adsorption), oxyfuel combustion, membrane separation, and cryogenic distillation. The selection of technology depends on a few factors such as the chemical composition and pressure of the gas stream, concentration of CO_2 in the gas stream, and the cost of technologies. Available CO_2 capture technologies are listed in **Table 2**.

Summary of the staff literature review on CCS economics

The CCS full value chain cost includes all costs associated with capture, transport, and storage of CO_2. CCS cost can be categorized as capital (equipment, labor, land, supporting facilities, permitting, financing & insurance), O&M cost (O&M labor, fuel, and other consumables), and other cost related elements (discount rate, interests, capacity factor & plant lifetime). The CCS cost is quantified as the difference between a facility without CCS and an equivalent facility with CCS.

The upfront capital cost for natural gas power plants can be hundreds of millions of dollars. Adding CCS to a natural gas plant can double the capital cost of the plant. The capital cost contributes to less than 30% of the levelized electricity cost. The cost of CO_2 capture ranges from 48 to104 $/metric ton, and the cost of avoided CO_2 emission ranges from 58 to 121$/metric ton. Adding CCS would add 2- 5 cent/kWh to the electricity cost.

Table 2: CO_2 capture technologies

Capture technology	Description	Status
Chemical solvent absorption	Uses solvent such as Amine to absorb CO_2 from the gas stream; the CO_2 is then stripped out of the solvent by direct contact with hot steam	Commercialized in certain applications such as natural gas processing; not commercialized for power plants.
Physical sorbent	A physical sorbent consists of small porous particles, which can selectively adsorb or form a complex with CO_2 to remove it from the gas stream. Pressure change and heat can regenerate the sorbent.	Commercially used in hydrogen production for refineries; can be used in pre-combustion and similar applications; pre-combustion capture involves converting fuels to a mixture of H_2 and CO_2, which has a high pressure and concentration of CO_2, and the CO_2 is less costly to capture; to be commercialized in power plants.
Oxyfuel combustion	Uses pure O_2 rather than air to combust fuels; the gas stream after combustion is a mixture of steam and highly concentrated CO_2; the CO_2 can be captured through distillation.	In the demonstration stage, and is yet to be commercialized in power plants and other industrial applications; has the potential for cost savings in applications such as cement industry, where a significant portion of CO_2 in the gas stream is from non-combustion processes.
Membrane CO_2 separation	Uses a very thin membrane to separate CO_2 from other gas components	Not commercialized for CCS
Cryogenic distillation	A gas is made liquid by a series of compression, cooling and expansion steps; once in liquid form, the components of the gas can be separated in a distillation column.	Not commercialized for CCS

The upfront capital cost for coal plants can be hundreds of millions to a billion. The capital cost can contributes to more than 50% in the levelized electricity cost. The cost of CO_2 capture ranges from $36/metric ton to 53 $/metric ton, and the cost of avoided CO_2 emission ranges at 45–70$/metric ton. Adding CCS would add 3-7 cent/kWh to the electricity cost, which is more than the increase in cost of electricity for natural goas because coal generates more CO_2 per kWh than natural gas.

The CO_2 capture costs for different industry sectors can vary significantly depending on the production processes. For processes producing highly concentrated CO_2 as a byproduct, such as natural gas processing, hydrogen production and ethanol production, the CO_2 capture is less costly representing some “low hanging fruit” opportunities for CCS. For some other industrial sectors, such as cement, iron and steel, and refineries with multiple small CO_2 streams, there is a lack of demonstration projects and the CO_2 capture cost is perceived to be significantly higher. For small CO_2

emitters that are far from the storage site, CCS cost can be prohibitively high due to the lack of economies of scale. **Figure 2** shows the capture cost for a range of industry sectors.[45]

Transportation and storage costs highly depend on the distance between emission sources and storage sites, volume of CO_2 emissions (affect economies of scale), and the utilization of pipelines (underutilization increases transportation and storage cost). Additionally, there is cost associated with monitoring, and post-injection site care.

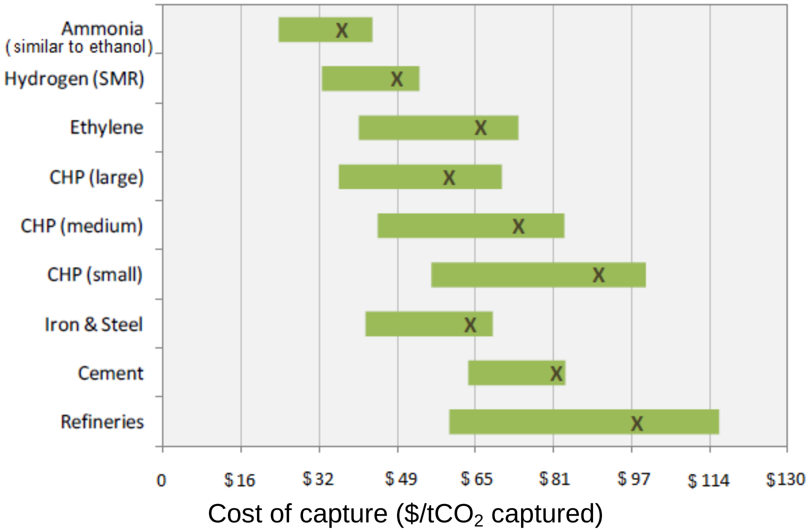

Figure 2: range of modeled capture costs in 2030 (modified from: element energy, 2010)[46]

Existing Projects

ARB staff gathered information on major CCS projects in the world. **Table 3** shows the large scale CCS projects that are currently in operation or set to become operational in the next 1-2 years, and are sequestering about 1.0 MMT CO_2/yr. The majority of these are CO_2-EOR projects; large-scale saline storage projects are still limited. One example of a large-scale saline storage project in operation is the Shell Quest project in Alberta, Canada. There are also multiple completed large CCS projects. The Weyburn-Midale project previously captured 3.0 MMT CO_2/yr, was completed in 2012, and is currently undergoing post-injection monitoring. Injection at the 1.0 MMT CO_2/yr In Salah project in Algeria was temporarily suspended in 2011 in order to reevaluate injection strategy.

---

[45] Element Energy Limited, Potential for the application of CCS to UK industry and natural gas power generation: Issue 3, 2010, Cambridge, UK.

[46] Note: capture cost ranges calculated based on low, central (with markers), and high UK industrial energy price forecasts; US cost may be lower due to lower energy cost; U.S. Treasury Department's 2009 Currency Exchange Rate is used for converting currency. Refineries costs do not include onsite SMR.

Table 3: Large-scale CCS projects

Project Name	Location	Operational date	CO_2 source	Capture type	Capture capacity (MMT CO_2/yr)	Sequestration type	Status
Century Plant	Texas	2010	Gas Processing	Pre-combustion	8.4	CO_2-EOR	Operational
Shute Creek/La Barge	Wyoming	1986	Gas Processing	Pre-combustion	6.0	CO_2-EOR	Operational
Gorgon	Australia	2017	Gas Processing	Pre-combustion	3.4 – 4.0	Saline	Future
Kemper County	Mississippi	2016	Power Generation	Pre-combustion	3.0	CO_2-EOR	Future
Weyburn-Midale	Saskatchewan	2000	Coal Gasification	Pre-combustion	3.0	CO_2-EOR	Completed
Alberta Carbon Trunk Line	Alberta	2016 – 2017	Refining; Fertilizer Production	Industrial Separation	1.7	CO_2-EOR	Future
Petra Nova	Texas	2016 – 2017	Power Generation	Post-combustion	1.4	CO_2-EOR	Future
Val Verde	Texas	1972	Gas Processing	Pre-combustion	1.3	CO_2-EOR	Operational
In Salah	Algeria	2004	Gas Processing	Industrial Separation	1.2	Depleted Gas	Suspended
Boundary Dam	Saskatchewan	2014	Power Generation	Post-combustion	1.0	CO_2-EOR	Operational
Quest	Alberta	2015	Steam Methane	Industrial Separation	1.0	Saline	Operational
Port Arthur/Air Products	Texas	2013	Steam Methane	Industrial Separation	1.0	CO_2-EOR	Operational
Lost Cabin	Wyoming	2013	Gas Processing	Pre-combustion	1.0	CO_2-EOR	Operational
Coffeyville	Kansas	2013	Fertilizer Production	Industrial Separation	1.0	CO_2-EOR	Operational
Illinois Industrial	Illinois	2017	Ethanol Production	Industrial Separation	1.0	Saline	Future
Sleipner	Norway	1996	Gas Processing	Industrial Separation	0.85-1	Saline	Operational

Next Steps

During 2016, staff efforts were been primarily focused on increasing knowledge and soliciting stakeholder concerns and public comments on specific topics related to CCS. Staff has completed this phase of the project through a workshop, six technical discussions, numerous stakeholder meetings, research, and site visits. The next phase of the development of the CCS QM and Permanence Protocol will be to develop concept papers, hold workshops, and release draft documents for the CCS QM and Permanence Protocol. Staff plans to develop final drafts of the QM by Q3 or Q4 of 2017. These documents would then be considered for inclusion in the LCFS rulemaking in a board hearing in early 2018. The Cap-and-Trade program would adopt the QM and Permanence Protocol at a future date as part of an amendment, likely no earlier than 2020. All of these timeframes are subject to change due to stakeholder interaction and feedback as well as at the discretion of the LCFS and Cap-and-Trade program scheduling needs. **Figure 3** shows the timeline of future CCS related activities.

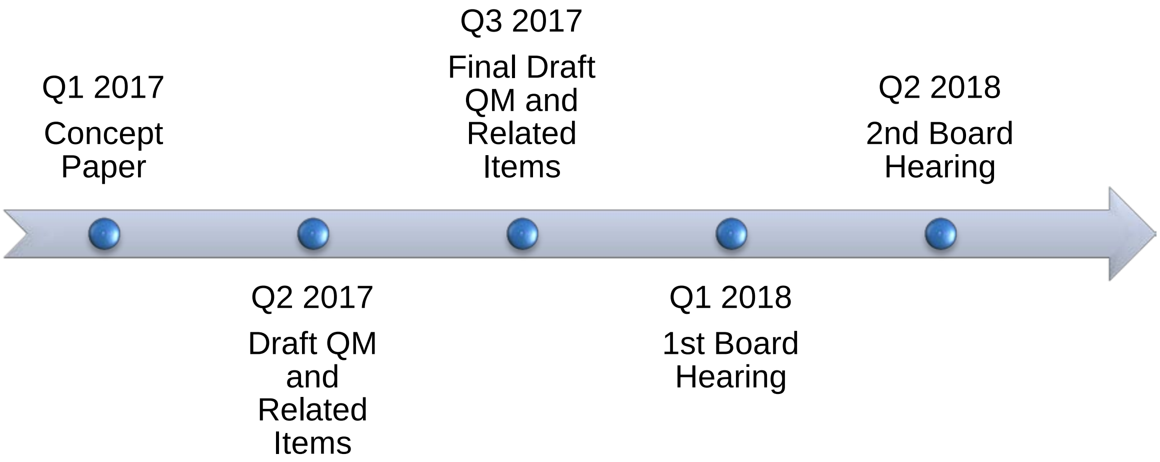

Figure 3: the timeline of future CCS related activities

Contacts:

For questions or feedback on this document please contact:

Alexander “Lex” Mitchell, Manager, Emerging Technology Section
Alexander.Mitchell@arb.ca.gov; 916-327-1513.

Or

Xuping Li, Air Resources Engineer
Xuping.Li@arb.ca.gov; 916-322-9148.