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**Review of Quantitative Monitoring Methodologies for
Emissions Verification and Accounting for Carbon Dioxide
Capture and Storage for California's Greenhouse Gas Cap-
and-Trade and Low-Carbon Fuel Standard Programs**

**Final Report
Deliverable under
ARB Agreement No. 12-411**

**Prepared for the California Air Resources Board and the
California Environmental Protection Agency**

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December 23, 2014

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ABSTRACT

The Cap-and-Trade and Low Carbon Fuel Standard (LCFS) programs being administered by the California Air Resources Board (CARB) include Carbon Dioxide Capture and Storage (CCS) as a potential means to reduce greenhouse gas (GHG) emissions. However, there is currently no universal standard approach that quantifies GHG emissions reductions for CCS and that is suitable for the quantitative needs of the Cap-and-Trade and LCFS programs. CCS involves emissions related to the capture (e.g., arising from increased energy needed to separate carbon dioxide (CO₂) from a flue gas and compress it for transport), transport (e.g., by pipeline), and storage of CO₂ (e.g., due to leakage to the atmosphere from geologic CO₂ storage sites). In this project, we reviewed and compared monitoring, verification, and accounting (MVA) protocols for CCS from around the world by focusing on protocols specific to the geologic storage part of CCS. In addition to presenting the review of these protocols, we highlight in this report those storage-related MVA protocols that we believe are particularly appropriate for CCS in California. We find that none of the existing protocols is completely appropriate for California, but various elements of all of them could be adopted and/or augmented to develop a rigorous, defensible, and practical surface leakage MVA protocol for California. The key features of a suitable surface leakage MVA plan for California are that it: (1) informs and validates the leakage risk assessment, (2) specifies use of the most effective monitoring strategies while still being flexible enough to accommodate special or site-specific conditions, (3) quantifies stored CO₂, and (4) offers defensible estimates of uncertainty in monitored properties. California's surface leakage MVA protocol needs to be applicable to the main CO₂ storage opportunities (in California and in other states with entities participating in California's Cap-and-Trade or LCFS programs), specifically CO₂-enhanced oil recovery (CO₂-EOR), CO₂ injection into depleted gas reservoirs (with or without CO₂-enhanced gas recovery (CO₂-EGR)), as well as deep saline storage. Regarding the elements of an effective surface leakage MVA protocol, our recommendations for California are that: (1) both CO₂ and methane (CH₄) surface leakage should be monitored, especially for enhanced recovery scenarios, (2) emissions from all sources not directly related to injection and geologic storage (e.g., from capture, or pipeline transport) should be monitored and reported under a plan separate from the surface leakage MVA plan that is included as another component of the quantification methodology (QM), (3) the primary objective of the surface leakage MVA plan should be to quantify surface leakage of CO₂ and CH₄ and its uncertainty, with consideration of best-practices and state-of-the-art approaches to monitoring including attribution assessment, (4) effort should be made to monitor CO₂ storage and migration in the subsurface to anticipate future surface leakage monitoring needs, (5) detailed descriptions of specific monitoring technologies and approaches should be provided in the MVA plan, (6) the main purpose of the CO₂ injection project (CO₂-EOR, CO₂-EGR, or pure geologic carbon sequestration (GCS)) needs to be stated up front, (7) approaches to dealing with missing data and quantifying uncertainty need to be described, and (8) post-injection monitoring should go on for a period consistent with or longer than that prescribed by the U.S. EPA.

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EXECUTIVE SUMMARY

Background

The State of California's Assembly Bill 32 (AB 32) aims to reduce net greenhouse gas (GHG) emissions through a variety of means including the California Air Resources Board's (CARB) Cap-and-Trade and Low Carbon Fuel Standard (LCFS) programs, both of which may involve carbon dioxide (CO₂) capture and storage (CCS) as the means by which emissions are reduced. As a new technology not yet carried out widely, there is a need for monitoring, verification, and accounting (MVA) of CO₂ emissions especially related to geologic carbon sequestration (GCS, the geologic storage part of CCS). In order to ensure specified emissions caps are met, and that any emissions reductions associated with stored CO₂ represent real emission reductions, it is essential that geologic storage sites be monitored to ensure that no surface leakage is occurring, or if surface leakage is occurring, to quantify it. Several MVA protocols have been developed around the world for GHG reduction programs, with some components relevant to leakage from geologic storage sites. In addition, the U.S. EPA has developed regulations for CO₂-injection well permitting and GHG emissions reporting related to CO₂-enhanced oil recovery (CO₂-EOR) and GCS. The purpose of this project was to review existing MVA protocols, evaluate their various components, and recommend specific elements of surface leakage MVA protocols that would be particularly appropriate for implementation in California's Cap-and-Trade and LCFS programs.

Methods

The approach we took was a literature review of publications and reports on GHG reduction protocols, monitoring approaches, and regulations associated with CO₂ injection. We extracted and summarized GCS monitoring-specific information from the literature on MVA protocols that could be useful for defining a surface leakage MVA protocol tailored to conditions and opportunities in California. We summarized the major and detailed monitoring elements of these existing protocols through narrative summaries, and in two tables. To summarize the recommendations for California, we made two California-specific tables with annotations for the major and detailed elements that we had defined for the existing MVA protocols.

Results

We found that the existing MVA protocols we reviewed are defensible and stand on their own merits, but that no single protocol should be applied as-is to California. Instead, various pieces of the protocols can be selected and combined to create a rigorous and defensible California-specific GCS surface leakage MVA protocol, which would guide development of individual surface leakage MVA plans. California is developing policy objectives to ensure that: (i) the MVA results will inform and validate the leakage risk assessment; (ii) monitoring will be appropriate for each site; (iii) surface leakage, if any, can be quantified; and that (iv) uncertainty in potential surface leakage can be accurately estimated. For the above California-specific set of conditions, we recommend that separate MVA protocols be developed for CCS-related emissions not directly related to the geologic storage part of CCS¹, and that surface leakage of

¹ Emissions from all sources not directly related to injection and geologic storage (e.g., from capture, or pipeline transport) should be monitored and reported under a plan separate from the surface leakage MVA plan that is included as another component of the QM.

both CO₂ and methane (CH₄) be monitored to account for potential deep-sourced CH₄ contributions to GHG emissions. We further recommend that there should be flexibility to modify surface leakage MVA plans with periodic CARB review and re-approval. Quarterly reporting is recommended in the early stages of projects (first five years) and with approval from CARB, annually after that if operations do not result in leakage, creation of leakage pathways, or migration of CO₂ out of the planned storage complex. The option of discounting may be considered at the discretion of CARB as a potential mechanism to address uncertainty while also allowing operators flexibility in monitoring resource allocation. We suggest that, at least initially until GCS becomes more widespread, no lower-bound reporting threshold should be established (i.e., all detected CO₂ and CH₄ surface leakage should be reported with discrimination between shallow biogenic and deep-sources for the CO₂ and CH₄). The main objective of monitoring under the surface leakage MVA plan are to quantify surface leakage from the deep storage complex, and to quantify underground leakage and migration of CO₂ within and away from the storage complex insofar as such migrations may lead to surface leakage.

Quantifying surface leakage will require approaches such as open-path laser systems that can detect CO₂ and CH₄ concentration anomalies above background levels, which can point operators to regions where more detailed monitoring to estimate emission fluxes can be carried out. In addition to surface monitoring, the plan should include monitoring of the injection and migration processes in the reservoir (e.g., through sampling from observation wells or downhole or surface geophysical methods) to a degree that can serve to verify that storage is occurring, and provide information on unexpected or potentially problematic movement of CO₂ within or out of the storage zone.

The specification of monitoring approach needs to be sufficiently detailed such that an expert in GCS monitoring can review the plan, understand the monitoring rationale, and confirm its intended effectiveness. Some elements of the monitoring approach that should be discussed include, but are not limited to: overall approach to surface and subsurface monitoring; type of baseline monitoring; technology to be used; area to monitor; frequency of measurement; spatial coverage in terms of both region and intensity (e.g., number of points per area of ground); schedule of monitoring, including phased approaches for different project phases; attribution assessment and related monitoring, proxy and/or companion gas monitoring; and use of gas or groundwater tracers. Insofar as the U.S. EPA may also specify surface air or soil-gas monitoring as part of the Underground Injection Control (UIC) approval process, the surface leakage MVA protocol for California needs to be closely integrated and consistent with U.S. EPA's UIC and Mandatory Reporting of Greenhouse Gases Subparts RR² and UU³ requirements. As for the purpose of CO₂ injection, CARB needs information about whether the CO₂ injection is primarily for EOR, EGR, or GCS in order to account for the different operational and reservoir processes associated with enhanced recovery compared to pure GCS. Approaches to missing data, estimating emission detection limits, and quantifying uncertainty should be based on best practices and/or well-known and accepted approaches. Finally, post-injection monitoring

² This rule requires reporting of GHGs from facilities that inject carbon dioxide underground for geologic sequestration. Geologic sequestration (GS) is the long-term containment of carbon dioxide in subsurface geologic formations.

³ This rule requires reporting of GHGs from facilities that inject carbon dioxide underground for the purposes of enhanced oil and gas recovery or any other purpose other than geologic sequestration. Facilities that report under subpart RR for a well or group of wells are not required to report under subpart UU for that well or group of wells.

frequency should be at least as stringent as the agreed-upon post-injection site care (PISC) monitoring requirements negotiated between the operator and the U.S. EPA UIC program.⁴ The implication of this work for CARB is that our recommendations can serve as a starting point for CARB’s development of surface leakage MVA protocols for California’s Cap-and-Trade and LCFS programs. Given the many opportunities in California and other states for CO₂-EOR, and the importance of CH₄ as a potent GHG, we recommend that special consideration (e.g., inclusion of CH₄ surface leakage monitoring in addition to CO₂ monitoring) should be given to CO₂-EOR, or any injection into depleted oil or gas reservoirs, carried out with intended GHG reduction purposes.

Conclusions

A number of MVA protocols have been reviewed and evaluated for relevancy in order to inform development of a California-specific surface leakage MVA plan. None of the individual protocols has all of the elements needed for California; however, selected major and detailed elements can be borrowed from existing protocols to create a recommended set of surface leakage MVA elements. These recommended elements can be combined together to create a rational, rigorous, and defensible surface leakage MVA protocol. Future work should focus on emissions related to other parts of the CCS carbon life cycle, integration with MVA rules in other states, and leakage mitigation/contingency response.

⁴ Under the U.S. EPA’s UIC program, PISC must continue for a timeframe established in the permit (i.e., the 50-year default or an alternative timeframe established by modeling) or until the owner or operator can demonstrate to the UIC Program Director, based on site monitoring data, that the project no longer poses a risk of endangerment to underground sources of drinking water.

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1. INTRODUCTION

Background and Scope

AB 32, signed into law in 2006, called on CARB to develop a Scoping Plan outlining the State's strategy to achieve the target of reducing GHG emissions to 1990 levels by 2020. The initial AB 32 Scoping Plan, developed by CARB in coordination with the Climate Action Team (CAT), proposes a comprehensive set of actions designed to reduce overall GHG emissions in California. One of these strategies, referred to as "cap-and-trade," establishes an upper limit on the State's total GHG emissions, allows for the issuance of offset credits for offset projects that meet specific requirements in the Cap-and-Trade Regulation, and establishes markets for trading and selling allowances and offset credits. The Cap-and-Trade Regulation states that CO₂ suppliers may reduce their compliance obligation for each metric ton of CO₂ that has been proven to be sequestered using a Board-approved CCS quantification methodology (QM). In California, any entity involved in capturing and supplying CO₂ to another entity is regulated as a CO₂ supplier. A second strategy identified in the Scoping Plan, the Low Carbon Fuel Standard (LCFS) program, provides financial incentives for companies to supply fuel to California's market that has demonstrably lower full fuel-cycle carbon intensity. Under the LCFS program, a regulated party may receive credit for fuel that is sold, supplied, or offered for sale in California and produced from petroleum using an innovative method such as CCS. The Cap-and-Trade and LCFS programs are complementary.

Monitoring that is accurate, precise, and timely is critical to the success of any approach to reducing GHG emissions that involves establishing limits on emissions. Accuracy is needed because the public and industry need to be assured that programs and strategies are achieving their objective, which is to reduce the State's net GHG emissions. Precision is needed because emissions need to be translated into quantifiable amounts appropriate for meeting pre-defined limits and for fair trading of emissions credits. Timeliness is needed because caps are often set for emissions over defined periods, and it is necessary to quantify emissions or verify inventory over these same periods.

The initial AB 32 Scoping Plan identifies CCS as a technology that can be used for reducing CO₂ emissions under the Cap-and-Trade program. In addition, under the LCFS program, CCS can reduce fuel-cycle carbon intensity (e.g., through the capture and sequestration of CO₂ generated during biofuel production, or through the use of CO₂-EOR). In general, CO₂ injected into deep geologic formations under a thick impermeable cap rock can be expected to be isolated from the atmosphere indefinitely (IPCC, 2005). The concern is that, in some cases, wellbores, or previously unrecognized fast-flow pathways upward from the deep subsurface, may allow CO₂ leakage out of the storage region and into the atmosphere. Assurance that atmospheric emissions, also referred to as "surface leakage," from deep CO₂ storage sites is not occurring, or the quantification of surface leakage if it is occurring, is essential to the accounting of GHG emissions for California's Cap-and-Trade and LCFS programs.

CCS typically involves the energy-intensive process of capturing CO₂ from flue gas, transporting it to the storage field, and injecting and storing CO₂ in the deep subsurface. As such, CCS brings a host of challenges to the monitoring imperative. The GHG emissions per usable energy unit must be calculated, taking into account additional emissions due to the operation of capture, transport, and storage facilities. For instance, the capture part of CCS

involves an energy penalty (i.e., the need to use additional thermal or electrical energy to run the capture plant and other CCS-related processes such as compression of CO₂ for pipeline transport). The energy penalty will vary depending on whether CO₂ is captured from power plants, oil refineries, cement plants, or other facilities, and the types of fuel and process used at the various plants. For coal-fired power plants, the energy penalty is estimated to average approximately 40%, but ranges from approximately 25-80% depending on whether the plant is retrofitted or built for capture (House et al., 2009). The extra energy used to satisfy the energy penalty, assuming it is generated by fossil fuel combustion, will cause additional atmospheric emissions from surface sources that must be accounted for and managed. These emissions arise from the fact that capture will not be 100% effective at the power plant, from external sources related to the need to produce more fossil fuel (e.g., hydrocarbon production and transportation) to supply the extra energy needed for CCS, and from the production of infrastructure and consumables (e.g., capture solvents) for CO₂ capture, transportation, and injection. These additional external emissions are not captured by the CCS facility at the plant and therefore should be subtracted from a facility's emissions reductions to calculate a baseline against which credits are issued. In this study, we do not consider emissions related to the energy penalty or other indirect emissions, but rather we focus directly on monitoring of emissions arising from surface leakage from the geological storage sites (i.e., surface leakage of CO₂ and CH₄ from the deep subsurface to the atmosphere).

The storage part of CCS, referred to herein as GCS, involves injection of compressed CO₂ into deep saline formations or depleted oil or gas reservoirs. Compared to emissions accounting for capture and transport operations, there is greater uncertainty in GCS accounting due to its substantial dependence on natural rather than engineered systems. In particular, the containment of CO₂ in geologic storage sites relies on natural cap rocks and a variety of natural trapping mechanisms (IPCC, 2005). While a large amount of research is being carried out to understand the long-term trapping and containment processes associated with sequestered CO₂, the fact is that there is not a long track record of surface leakage monitoring of GCS. What this means is the likelihood and extent of emissions (i.e., surface leakage) into the atmosphere (e.g., through old well bores or unidentified faults or fracture zones) is not well known. While approaches to monitoring for such leakage have been proposed and evaluated (e.g., Oldenburg et al., 2003; IPCC, 2005; Plasynski et al., 2011), actual monitoring experience is very limited.

The overall process of quantifying GHG emission reductions under market-based mechanisms, such as California's Cap-and-Trade and LCFS programs, by CCS or any other means, is referred to as monitoring, verification, and accounting (i.e., MVA). Activities in MVA can occur at all levels in the energy life cycle from production of primary fuel sources, to end use of energy by the consumer, to emissions of flue gas, disposal of waste products, and storage of CO₂. As such, MVA involves a wide variety of activities and disciplines with varying approaches depending on the point in time that they are carried out in the life cycle. In this report, we define the terms behind MVA more narrowly (see *Definitions*, below) to focus on the geologic storage component of GHG emissions reduction.

Regulatory Context

Section 95852(g) of the Cap-and-Trade Regulation currently acknowledges the potential for emissions reductions from CCS, and states that CO₂ suppliers (covered entities) may reduce

their compliance obligation for each metric ton of CO₂ that has been proven to be sequestered using a Board-approved CCS quantification methodology.

Section 95101 of the Mandatory Reporting Regulation (MRR) states that operators of facilities that engage in injection of CO₂ are subject to reporting under MRR regardless of their emissions levels. Section 95101 also states that any entity involved in capturing and supplying CO₂ to another entity is regulated as a CO₂ supplier and subject to MRR reporting requirements without regard to quantity produced.

Under the LCFS program, a regulated party may receive credit for fuel that is sold, supplied, or offered for sale in California and produced from petroleum using an innovative method such as CCS. The credit calculation for fuels derived from petroleum feedstock which is produced using innovative methods such as CCS is specified in section 95486(b)(2)(A)4 of the LCFS Regulation.

Objective

The objective of this report is to carry out a technical evaluation of existing CCS GHG quantification methodologies for GHG emissions and inventory accounting related to the geologic storage component of CCS. The review encompasses methodologies from around the world. However, the emphasis is on evaluating methods appropriate for CO₂ injection within California given California's geology and hydrology characteristics and the potential for subsurface-to-atmosphere leakage. Notwithstanding the California emphasis, eligible projects may occur outside of California and the MVA protocols should be able to accommodate the geologic conditions in other states. The MVA protocol should also be developed with awareness to MVA protocols used in other states and nationally and consider best practices. The results of the evaluation presented here are intended to be used by CARB to inform the development of policy and protocols for MVA for the geologic storage part of CCS, with specific focus on California's Cap-and-Trade and LCFS programs.

Approach

The main approach to accomplish the project objective is literature review of existing GCS-related MVA approaches, with an emphasis on those most relevant to CCS in California. All of the literature we reviewed was freely available from the world-wide web. Two potentially relevant documents required payment and were not obtained (ISO 14064-2:2006 (\$65), and the Canadian Standards Association Z471-12 (\$153)). However, the Indian government's GHG inventory and reduction reporting program, which purports to be identical to the ISO 14064-2 standard, was independently obtained via free distribution (Bureau of Indian Standards, 2006).⁵

Definitions

While the terms monitoring, verification, and accounting all have well-known vernacular meanings, it is important at the outset to establish their meanings in the context of CCS, and in this sequestration-focused study in particular. In the broad context of CCS, the meanings of

⁵ We determined from a review of the Indian version of ISO 14064-2:2006 that the protocol is too general to be of use in providing input for monitoring requirements for California and therefore a comprehensive review of this protocol was not included in this report. We note, however, that the PEW-C2ES protocol, which was reviewed in this report, maintains consistency with this standard.

monitoring, verification, and accounting are close to common usage, and refer, respectively, to the measurements used to quantify the effectiveness of the reduction of CO₂ emissions, to the confirmation that a given CCS strategy is occurring as planned and designed, and to the quantitative tracking of transported, captured, injected, and emitted CO₂. In the narrower context of the subsurface-storage component of CCS, the words take on narrower meanings, specifically as follows:

Monitoring: Refers to the process of making measurements and/or recording observations in the atmosphere, ground surface, shallow subsurface, or deep subsurface either locally at points or broadly over large areas to detect the actual or potential migration or leakage of CO₂. The observations can be discrete in time or continuous. Because surface leakage of CO₂ or CH₄ from the deep subsurface is not expected, monitoring of GCS sites is usually carried out in the context of assurance monitoring (i.e., with the objective of assuring that CO₂ is not leaking and that effective sequestration is occurring). An example of monitoring in the GCS context is the use of open-path laser techniques applied over the large area of the sequestration site designed to detect abnormal concentrations of CO₂ that could be indicative of CO₂ leakage into the atmosphere.

Verification: Refers to the quantitative confirmation that CO₂ injected for sequestration is being accommodated and effectively trapped in the intended subsurface reservoir. Elements of verification include estimates of storage capacity in the reservoir; comparison of actual and modeled injection performance (e.g., injection rate and pressure response); and comparison of actual and modeled fluid displacement, migration, and trapping behavior to validate the conceptual model of the storage reservoir. Verification relies heavily on deep subsurface monitoring to provide the actual performance data during the operational stages of a CCS project, and it relies more on surface and above-ground monitoring during the late and post-closure stages of a CCS project to verify storage.

Accounting: Refers to the process of the quantitative tracking of the CO₂ transfers (e.g., by pipeline, into injection wells, produced with oil during CO₂-EOR) and changes (presumably reductions) in emissions of CO₂ under a given CCS scenario. Accounting relies on accurate measurements using flow gauges (e.g., at pipelines and well heads) and gas analyzers (e.g., for flow in flue gas stacks or separation tanks). Accounting also relies on accurate chemical process modeling (e.g., to estimate emissions from combustion and chemical separation processes to use as proxies for measurements which may be impractical).

We note further that two other acronyms are also frequently used in addition to MVA, specifically: monitoring, reporting, and verification, or MRV; and measurement, monitoring, and verification or MMV. The only new terms here are “reporting,” whose meaning is self-evident, and “measurement,” which we take to be synonymous with monitoring.

Leakage Terminology

The term emissions leakage often refers to an increase in GHG emissions outside of a jurisdiction or region, resulting from a decrease in GHG emissions inside the jurisdiction or region. For example, emissions leakage occurs if a regulation requiring reduced GHG emissions in one region shuts down a manufacturing plant, which leads to increased manufacturing of the same product in another region (with the same or larger GHG emissions). In this case, GHG

emission decreases reported within the region are wholly or partially negated by GHG emission increases occurring elsewhere. In such cases, the overall global GHG reduction objective was not met due to emissions leakage.

In the context of GCS, the term leakage has a different meaning. The International Panel on Climate Change (IPCC) (Holloway et al., 2006) defines leakage in this context as the "...transfer of CO₂ from beneath the ground surface or sea bed to the atmosphere or ocean." The original draft of the European Union (EU) CCS Directive defined leakage similarly, but this was changed during negotiations (Tim Dixon, pers. commun.) to allow for the fact that leakage may or may not result in atmospheric emissions. For example, the EU CCS Directive states "Leakage" means any release of CO₂ from the storage complex" (EU, 2009). This indirectly defines leakage as CO₂ transport out of the storage region but not necessarily into the atmosphere. The EU CCS Directive states that "Migration means the movement of CO₂ within the storage complex." Finally, the United Nations Framework Convention on Climate Change (UNFCCC), also referred to as the Kyoto Protocol, defines seepage as "...a transfer of carbon dioxide from beneath the ground surface or seabed ultimately to the atmosphere or ocean" (UNFCCC, 2011).

We agree with the current EU definition which considers that CO₂ leakage may or may not result in atmospheric emissions for the following reasons. First, it will commonly be the case that more than one cap-rock seal will be present above the storage reservoir, such that if CO₂ unexpectedly migrates through the lower-most cap rock and into a secondary storage region (below the next shallower cap rock), the CO₂ will still be trapped deep underground. By this understanding, leakage from the storage region does not necessarily equate to atmospheric emissions. On the other hand, if CO₂ flows to a leaking well or the shallow subsurface, it can readily seep into the atmosphere. In short, leakage refers to migration of CO₂ out of the intended storage region, and seepage or surface leakage refers to emission into the atmosphere. These definitions as used by the EU were also proposed and used by us in previous work (e.g., Oldenburg et al., 2009). However, to avoid confusion, we recommend use of the term surface leakage as a synonym to seepage to indicate emissions to the atmosphere.

Existing Literature

There are published reports and papers that focus on monitoring technologies related to CCS as an approach to GHG emissions reduction. The most recent and comprehensive of these is the International Energy Agency Greenhouse Gas (IEAGHG) commissioned report authored by Korre et al. (2012), which provides an excellent summary and review of some of the most promising CO₂ monitoring and leakage detection technologies and approaches. They report that short and long open-path diode lasers and eddy covariance monitoring are effective atmospheric leakage detection and quantification approaches, reportedly capable of detecting leakage rates at the level of approximately 0.01% of the injected CO₂ per year. The open-path laser technique was confirmed to be very effective at detecting elevated CO₂ and CH₄ in actual gas-release field experiments, with greater ability to detect CH₄ anomalies due to the lower natural background variability in CH₄ relative to CO₂ (Trottier et al., 2009). Flesch et al. (2004) combined open-path laser measurements with atmospheric dispersion modeling to independently estimate a known tracer release rate. The advantage of atmospheric detection is that one does not have to know the exact location of the surface leakage in order to detect the emissions, but rather one can instead deploy the monitoring more broadly with the expectation of being able to detect

surface leakage from all of the potential leakage pathways. Once surface leakage is detected, more detailed investigations can be launched to locate and characterize the emission sources, and quantify the emission flux (Cortis et al., 2008).

One of the earliest reports is that of Oldenburg et al. (2003) who discussed the challenges of discerning a leakage signal from natural background variations in CO₂ fluxes, and reviewed monitoring approaches including stable and radiogenic carbon isotopic methods. A more recent comprehensive study (Plasynski et al., 2011) covers all aspects of MVA activities associated with geologic CO₂ storage projects, including site characterization, CO₂ plume tracking, CO₂ flow rate and injection pressure monitoring, leak detection, cap-rock integrity analysis, and long-term post injection monitoring. Plasynski et al. (2011) suggest that different stages of GCS site development have different needs for MVA activities that can be described by decision trees.

Wolaver et al. (2013) introduced the idea that different characterization, risk assessment, and monitoring approaches should be carried out depending on land-use history. The greenfield (i.e., “greensites”) and brownfield (i.e., “brownsites”) terminology is borrowed from the study of contaminant hydrology and risk assessment. Brownfield sites are those with prior history of industrial fluid production and/or injection (e.g., oil and gas fields), while greenfield sites are those with no such prior history. Brownsites will have legacy infrastructure and greater understanding of subsurface fluids and geology, but also strongly perturbed and evolving subsurface systems responding to fluid production or injection activities. Greensites will have sparse subsurface data, and no proven capacity for storage or containment. These differences must be taken into account when designing an effective MVA plan depending on the prior land-use at the site.

Schakenback et al. (2006) describe elements of cap-and-trade MRV that are credited with making cap-and-trade approaches regarding other atmospheric pollutants successful, such as the 1990 SO₂ part of the acid rain program and the 2003 NO_x budget trading program. The features of these prior programs include:

1. Incentives and automatic penalties to assure compliance;
2. Strong quality assurance (QA) checks;
3. A collaborative approach with a petition process (e.g., to U.S. EPA to clarify guidance);
4. Standardized electronic reporting; and
5. Compliance flexibility (e.g., to accommodate unexpected delays in reporting due to unforeseen changes in conditions or operations, as long as emission-reduction goals are not sacrificed).

As one of the most promising early deployment opportunities for GCS, CO₂-EOR has been the subject of prior work related to MVA. The interest in MVA for CO₂-EOR arises due to its complexity relative to other forms of GCS. Specifically, CO₂-EOR involves more complicated considerations of injection, sequestration, and net emissions reductions because a large fraction of the CO₂ that is injected is eventually produced with oil, separated from the oil, and re-injected. Melzer (2012) describes the similarity of surveillance tools and approaches for CO₂-EOR relative to standard GCS, and argues that despite the CO₂ recycle processes that are part of

CO₂-EOR, operators should be given credit for sequestering anthropogenic CO₂ utilized for EOR. This argument is based on the assumption that CO₂ will be effectively separated from produced oil and re-injected during operations, and most importantly, permanently trapped following CO₂-EOR operations. Although it is likely that CO₂ injected into oil or gas reservoirs will remain trapped, this argument is unlikely to persuade regulators about permanence or provide the rigor needed by a cap-and-trade or LCFS program, as these approaches demand a much higher level of MVA to ensure no re-entry of CO₂ into the atmosphere.

Hovorka (2010) recognized earlier that in order for CO₂-EOR to qualify for GCS credit, operators will have to report data that previously was considered proprietary, and they will have to measure and document permanence. Marston (2013) argues that current regulations for CO₂ storage do not reflect the realities of CO₂-EOR insofar as CO₂-EOR operations typically do not involve overall reservoir pressure increase because oil is produced simultaneously with CO₂ injection. While the U.S. EPA recognizes that geologic storage occurs in EOR projects, the U.S. EPA rules and Subpart UU requirements in particular do not provide an explicit mechanism for accounting for and verifying quantities of CO₂ stored during EOR unless operators choose to opt in to reporting under Subpart RR, the requirement for non-EOR storage projects (see summary of Subpart RR in Section 3). Marston (2013) concludes that this failure to require accounting of storage in CO₂-EOR will delay deployment of this useful CCS approach.

We note that insofar as CH₄ is also an important GHG, which is ubiquitous in oil and gas reservoirs, and also often present in deep brine formations (Kharaka and Hanor, 2007), the surface leakage of CH₄ related to CO₂ injection for EOR or GCS may be a significant factor in the evaluation of the net GHG reduction of the activity.

2. MATERIALS AND METHODS

Our literature review covered publications and reports on GHG reduction protocols and monitoring associated with CCS. Some of the literature covered monitoring technologies at a highly technical level, but this was not the emphasis of the current phase of the project. With literature on monitoring protocols in hand, the task was to extract and summarize GCS-monitoring-specific information that could be useful for defining monitoring protocols in California. We summarize the monitoring elements of these existing protocols through narrative and in Tables 1 and 2. In Tables 1 and 2, the rows comprise various protocol elements, and the columns comprise the GHG reduction protocols we reviewed. A short evaluative term or phrase was placed in the cell formed by the intersection of the various rows and columns.

The second phase of the project was an analysis effort in which we evaluated the various monitoring approaches in light of California-specific needs and requirements. The outcome of this analysis is a set of recommendations for California in the area of quantitative monitoring of CCS projects presented as narrative and in Tables 3 and 4.

3. RESULTS

Overview of Monitoring for GHG Reduction Protocols Involving CCS

United States Environmental Protection Agency Underground Injection Control Program

By the authority of the Safe Drinking Water Act, the U.S. EPA regulates subsurface fluid injection to protect Underground Sources of Drinking Water (USDW), defined as groundwater with less than 10,000 milligrams/liter (mg/L) total dissolved solids (TDS). Many states have been granted primary enforcement responsibility (primacy) by the federal government in regulating underground injection on their lands if they meet certain requirements (U.S. EPA, 2014). The U.S. EPA's UIC program classifies underground fluid injection into six well classes on the basis of the kind of fluid and purpose of injection:

Class I: Hazardous industrial and municipal wastes

Class II: Fluids related to oil and gas production

Class III: Solution mining (e.g., salt and uranium)

Class IV: Shallow hazardous waste—only for remediation activities

Class V: Shallow injection of nonhazardous fluids

Class VI: Geologic sequestration of CO₂

Although the UIC program is designed to protect groundwater quality, Classes II and VI are relevant to California Cap-and-Trade and LCFS because both of these well classes may involve injection of CO₂ and associated sequestration of CO₂. In order to protect USDW, Class II and Class VI wells and the geologic environment of the injection zone must meet various requirements (U.S. EPA, 2012, 2013a, 2013b). For Class II wells, three layers of protection between the well and the formation are required (surface casing, production casing, injection tubing string and packer). In addition, Class II wells must pass a mechanical integrity test (MIT) every five years. For Class VI wells, requirements are considerably more stringent and include multiple well-integrity requirements, and post-injection site care (PISC) for a period of 50 years, or as agreed to by the UIC Program Director. Both Class II and Class VI wells require consideration of an Area of Review (AoR), which is defined as the area under which the injection formation is pressurized by the injection to an extent large enough to lift fluid from the injection zone to the level of USDW, assuming a hypothetical open conduit. Existing Class II wells are assumed to have a ¼-mile AoR. New Class II wells and Class VI wells require a calculation of AoR based on the estimated injection pressure and properties of the injection zone. Within the AoR, all features that could provide a flow path for fluid from the injection zone to the USDW must be identified. These features include existing wells (producing, injecting, idle, or abandoned), surface water bodies, mines and quarries, residences and roads, and known faults. For all wells deemed to be likely migration pathways, a corrective action (CA) plan is required which may include plugging and abandoning the well (U.S. EPA, 2013c). For Class VI wells being used for large-scale GCS, the AoR may be hundreds of square miles due to the potentially large pressure rise caused by injecting large volumes of CO₂, thereby

making the identification, and even more importantly the CA of wells within the AoR, a difficult and expensive task. It is important to note that the AoR will normally be much larger than the areal extent of the subsurface CO₂ plume which is the concern for surface leakage of CO₂.

Because of the focus on requirements aimed at ensuring protection of USDW, both Class II and Class VI regulations enhance the likelihood that CO₂ injected into these wells will remain in the subsurface with no surface leakage for 100 years or more. Nevertheless, the degree to which such implicit assurance, secondary to USDW protection, is provided differs greatly between the two well classes. In particular, Class II wells, in the context of this report, are used for CO₂-EOR, a process by which CO₂ is injected for enhancing oil recovery.⁶

In CO₂-EOR, oil with dissolved and/or free-phase CO₂ is produced (i.e., brought to the surface) in nearby wells and the mixture is sent through a separator where the CO₂ is separated to be re-used for injection. Suffice it to say there are several opportunities within the surface infrastructure of pipelines, valves, meters, separators, wellheads, etc. for CO₂ emissions to enter the atmosphere in the process of repeated cycles of CO₂ injection for EOR. However, another aspect of CO₂-EOR that favors sequestration of CO₂ is the implicit pressure control associated with continuous removal of mass from the reservoir in the form of oil (i.e., space is made in the reservoir for injected CO₂ by the production of oil). On the other hand, CO₂ storage integrity is threatened at EOR sites by high well density, aging well infrastructure, and potential lack of cooperation and information-sharing among operators of adjoining fields.

In contrast to CO₂-EOR, CO₂ injected for the purpose of GCS in saline aquifers under Class VI is injected into a storage region once and neither produced nor recycled. Furthermore, under Class VI, the storage region has been characterized to identify and mitigate potential pathways to the surface during the AoR delineation and CA process. The U.S. EPA maintains the right to specify surface air and/or soil-gas monitoring at the discretion of the UIC Program Director as part of its Class VI well approval process. In addition, the U.S. EPA has developed guidelines for the transitioning of Class II wells used for CO₂-EOR to Class VI wells used for GCS (U.S. EPA, 2013d). With the above discussion of differences in the protection of groundwater versus avoiding surface leakage in mind, the U.S. EPA has also developed draft monitoring regulations aimed at atmospheric emissions applicable to both CO₂-EOR and GCS operations in order to complement the UIC regulations, as discussed below.

U.S. EPA 40 CFR 98 Subparts UU&RR MRV

By the authority of the Clean Air Act, the U.S. EPA regulates all CO₂ injection facilities, whether they are for GCS or another purpose, such as CO₂-EOR. This regulation is for monitoring and reporting only, with Subpart RR applicable to sequestration, and Subpart UU applicable to injection of CO₂. The regulation requires reporting of leakage to the surface “in the event leakage occurs” and requires use of a mass balance approach “regardless of the class of UIC permit that a facility holds.”

⁶ We note that CO₂ may someday also be used for enhanced gas recovery (EGR), in which case the well that is used for injection would also be a Class II well, but because CO₂-EGR is not being carried out anywhere to our knowledge, we often refer only to CO₂-EOR in this report.

The Class VI site characterization and AoR modeling predictions can provide the basis for the Subpart RR MRV, which needs to specify how monitoring will detect and quantify surface leakage. If surface leakage monitoring was required under Class VI (this is at the discretion of UIC Program Director), then this monitoring must be approved by the Director for Subpart RR. There is an exemption for short-duration CO₂ injection if not commercial.

The Subpart RR and UU regulations require comprehensive monitoring (e.g., including reporting of percentage CO₂ remaining with oil or other fluids). Furthermore, there is the requirement to develop a plan for detecting and quantifying “air emissions.” The underlying approach required is mass balance [(CO₂ injected minus total emissions)/year]. There are five major components:

- 1) Delineation of maximum monitoring area (MMA) and active monitoring area (AMA). This component allows for phased monitoring.
- 2) Identification and evaluation of potential surface leakage pathways along with assessment of likelihood, magnitude, and timing of surface leakage through these pathways in the MMA.
- 3) A strategy for detecting and quantifying any surface leakage of CO₂ in the event leakage occurs.
- 4) An approach for establishing the expected baselines for monitoring CO₂ surface leakage.
- 5) A summary of considerations made to calculate site-specific variables for the mass balance equation.

Various attributes of the elements of this monitoring protocol are summarized in Tables 1 and 2, in terms of the main elements and detailed elements, respectively. The U.S. EPA Subpart RR and UU regulations are rigorous and consistent with the other protocols. In summary, the UIC Class II and Class VI injection regulations are complemented by the Subpart UU and RR regulations to avoid both groundwater contamination and surface leakage.

European Union Emissions Trading Scheme (EU-ETS)

The EU-ETS is a complex program involving a multitude of directives aimed at reducing GHG emissions that includes CCS as a potential approach. Because of the limited land area available in the EU and abundant oil and gas resources in off-shore environments, much of the discussion of CCS involves off-shore (subsea) GCS. For example, the EU CCS Directive 2009/31/EC (EU, 2009), amends earlier directives, describes CCS, and presents definitions (e.g., of “water column” which pertains to subsea storage and refers to water above the bottom sediments, and of “leakage” which refers to CO₂ transport out of the storage complex). The EU CCS Directive also mentions the requirement to obtain a permit and the need to withdraw the permit if the permitting agency has been notified of leakage or significant irregularities in storage. Paragraph 28 of the EU CCS Directive states that monitoring is essential to assess whether leakage is harming the environment or human health. The EU CCS Directive states that monitoring used to detect irregularities and/or harm to the environment or human health should be done on the basis of a Monitoring Plan. Paragraph 29 of the EU CCS Directive pertains to reporting, and states that the results of the Monitoring Plan should be submitted to the cognizant authority at least once a year. It also states that member states should inspect sites to ensure compliance and

that monitoring should be carried out at a reduced level after transfer of responsibility (i.e., post-closure), but intensified if leakage is identified. Article 13 of the EU Directive refers to the need to compare model results to monitoring results, and refers to monitoring under the plan pursuant to requirements in Annex II. Annex II then lays out the requirements that both: (i) the monitoring parameters need to be specified, and (ii) the monitoring technology needs to be specified, without prescribing any of these parameters or technologies. Item (j) of Annex II mentions technology to detect migration, and item (l) mentions widespread coverage to detect leakage pathways not specifically identified. The EU CCS Directive states that the Monitoring Plan should be compared to modeling, with appropriate updates to both model and plan depending on results. In summary, this directive specifies that a Monitoring Plan must be developed, that monitoring must be carried out, that the results of monitoring should be compared to modeling, and that monitoring intensity should be increased if irregularities are detected. The background and further details on the overall monitoring methodologies that underlie the language of the EU-ETS are presented in Zakkour (2007).

A later amendment to the EU CCS Directive (2010), includes language pertaining to definitions of “leakage” and “emission.” Specifically, the EU CCS Directive (2010) states “Where leakages from storage complex pursuant to Directive 2009/31/EC are identified and lead to emissions...” then proceeds to list leakage as one potential source of emission along with fuel use, venting, etc. The EU CCS Directive then elaborates by stating that, “Monitoring shall start in the case that any leakage results in emissions...” The significance of these definitions is that, by using this language, the EU does not generally equate leakage with emissions. In other words, leakage occurs when CO₂ leaves the storage reservoir, but this CO₂ is not assumed a priori to reach the atmosphere as an emission. Only in the subsea (i.e., water column) case do they equate leakage with emission. The assumption here is that any CO₂ that enters the sea can relatively quickly be transported to the sea surface where it can enter the atmosphere as an emission.

We believe the above language and definitions are very significant and imply that leakage of CO₂ into deep aquifers does not necessarily have to count as an emission. This is rational and scientifically defensible on the grounds that leaking CO₂ from well-chosen CCS sites will very likely be trapped in secondary formations and not be emitted to the atmosphere for millennial time scales or longer, even if it leaves the storage complex.

The EU CCS Directive (2010) further describes the ways that emissions should be calculated from capture, transport, and storage activities. With respect to potential emissions, emissions from storage, fuel use, fugitive emissions at injection, production of CO₂ in EOR, and leakage from the storage complex are all considered. Regarding leakage from the storage complex, the document again makes it clear that leakage does not necessarily imply emission. Regarding monitoring approaches, the EU CCS Directive (2010) specifies the need to measure CO₂ leaked per hour, which may be averaged over 24 hours.

Document EU No. 601 (EU, 2012) presents an update to the monitoring and verification regulations, based on experience from 2008-2012. This document forms the emissions regulation and applies to all sources of emissions (e.g., combustion, including aviation, or calcination). The main requirements are that every emitter must have a monitoring plan that they implement, and that every emitter must interact with the competent authority on each element related to the plan. Missing data require the use of conservative estimates, with

calculation-based or measurement-based approaches allowed. Specifically, Article 22 states that if monitoring of actual CO₂ emissions due to leakage and seepage cannot be carried out to within 7.5% accuracy, then the estimated and reported emissions must be adjusted upwards by an amount equal to the actual measurement uncertainty (in percent) minus 7.5%. This provides an incentive to encourage operators to ensure monitoring accuracy of better than 7.5% of the actual emission rate.

We believe the EU monitoring approaches, to the extent they are specified, are reasonable and logical. The emphasis on off-shore CCS sites makes the discussion somewhat less relevant to California, where only onshore sites are considered. Tables 1 and 2 provide a summary in terms of the major and detailed elements.

Pew Research Center-Center for Climate and Energy Solutions (PEW-C2ES)

The PEW-C2ES framework (McCormick, 2012) describes methods for calculating emissions related to CCS projects and aims for consistency with the very general standard ISO 14064-2:2006 (Bureau of Indian Standards, 2009). Baseline (i.e., all non-CCS) emissions include both projection-based and performance standards-based approaches. A projection-based approach is one in which a comparison is made of emissions between a no-project case and the case with the proposed CCS project. A performance standards-based approach is one in which emissions are estimated on the basis of a performance metric (e.g., tonnes of CO₂ emitted per unit of output). The PEW-C2ES recognizes that determining emissions from capture, compression, transport, injection, and storage equipment is relatively straightforward, while monitoring and estimating emissions from geologic storage is novel with no extant, well-established standards. The protocol does not prescribe any specific approach and recognizes the need for fit-for-purpose monitoring plans consistent with EPA's Subpart RR MRV.

Under the PEW-C2ES framework, baseline emissions estimates must use either projection-based or standards-based approaches, and must take into account functional equivalence.⁷ The protocol uses CO₂e (carbon dioxide equivalent), but then ignores baseline CH₄ and N₂O emissions in the spirit of being conservative in the sense that under this assumption the baseline will have lower emissions than it might actually have. This assumption is conservative because the CO₂e counts all GHG emissions, and these are calculated relative to the baseline that ignores CH₄ and N₂O, making the ratio of CO₂e to baseline larger than it actually is. The approach suggests combining project emissions from Non-Producing (NP) and Producing (P) formations, as if the expectation is that both will be present at sites. Estimates of emissions from NP formations include leakage to the atmosphere "if it is detected" (McCormick, 2012), and estimates from P formations include CO₂ left in oil and transferred offsite.

Section 9.2.5 of the PEW-C2ES framework regards leakage to the atmosphere and requires project developers to quantify emissions from geologic storage reservoirs "...if they arise," thereby implicitly requiring surface leakage monitoring (McCormick, 2012). The framework states that detecting such leakage might involve comparing monitoring to modeling, and/or carrying out surface monitoring; however, no technologies are specified. Project developers and

⁷ Functional equivalence means that the baseline case and the project under consideration produce the same net beneficial outputs (e.g., of power or commercial product).

program authorities are directed to work together to establish CO₂ detection thresholds and ensure confidence in the ability to confirm storage effectiveness.

Appendix A presents four policy options to address potential reversals in emissions reductions from CCS projects. One option is that a percentage of all tons credited be discounted according to the likelihood of a reversal over a set period of time, referred to as “an assurance factor.” A second policy option is that a percentage of all tons credited be held in a reserve account, referred to as “holdbacks or buffer pools” (McCormick, 2012).

In the event that leakage from the storage complex happens, and that this leakage results in atmospheric emissions, project developers need to quantify the emissions according to the approach approved by project authorities. Program authorities could allow a write-off of stored CO₂ (i.e., a calculation based on a simplified estimation to conservatively determine maximum leakage) rather than rigorous quantification. Generally, estimating emissions will involve “...a sophisticated computation...” yet the Eq. 9 (identical to EPA’s Subpart RR) is very simple and does not elaborate an approach to estimate leakage along any particular pathway.

The PEW-C2ES framework describes the EU CCS Directive method (EU, 2009; 2010), which assumes that leakage occurred between the last time no leakage had been detected, up until the time at which previously detected leakage could no longer be detected. Other methods can be applied if approved by the competent authority. Under the PEW-C2ES framework, emissions shall be quantified with maximum overall uncertainty of $\pm 7.5\%$, consistent with the EU CCS Directive.

The PEW-C2ES framework also discusses the site-specific nature of surface leakage monitoring, and provides an overview of possible activities and their relevant times of implementation. Table 3 provides a useful list of published monitoring and best-practice manuals.

Overall, the PEW-C2ES framework handles GCS-related leakage in a rigorous manner consistent with the EU CCS Directive. The framework provides simple equations for all of the potential emissions sources. For GCS-related emissions, there is an assumption that surface leakage monitoring data are available, and an implicit acknowledgement that such data may not be continuous in time. As in the EU CCS Directive, if the uncertainty of monitoring of surface leakage is larger than 7.5%, then the assumed quantity of CO₂ emitted is augmented to account for the uncertainty.

American Carbon Registry (ACR)

The American Carbon Registry® (ACR) methodology (Blue Strategies, 2012) is based on the PEW-C2ES framework. In the ACR methodology, the project boundary is intentionally drawn broadly to avoid unaccounted emissions associated with capturing and storing CO₂. Specifically, it covers the full CCS value chain, including emissions from CO₂ recovery and re-injection operations at EOR and EGR sites. As for the temporal boundary, the minimum post-injection period for CCS projects is five years. The duration of post-injection monitoring can be extended beyond five years based on the monitoring results obtained during the initial five-year period and the project’s conformance to model predictions. This is also referred to as “conformance monitoring,” or the degree to which behavior of CO₂ in the injection zone within

the storage complex agrees with model predictions. If permanence cannot be assured based on the monitoring during this period, the project term will be extended in two-year increments until permanence is assured.

Like the PEW-C2ES framework, CO₂ emissions under the ACR methodology can be based on two alternative approaches: projection-based or standards-based. The emissions calculation procedures for CO₂ storage cover direct CO₂, CH₄, and N₂O emissions from stationary combustion; CO₂ and CH₄ emissions from venting and fugitive releases to the atmosphere; and indirect CO₂ emissions from purchased electricity use. The methodology also accounts for any CO₂ that is produced with the hydrocarbons and transferred offsite (i.e., incomplete CO₂ separation from oil) and leakage of injected CO₂ from the reservoir to the atmosphere.

Project developers must quantify fugitive CO₂ emissions from the geologic storage reservoir to the atmosphere, if they arise. Leakage shall be monitored during the entire project term including the injection period, and for the post-injection time-period during which the reservoir is monitored for leakage to the atmosphere (i.e., at least five years, with the potential for additional years of monitoring required based on conformance modeling). Detecting leakage from the geologic reservoir that could lead to atmospheric emissions might involve a comparison of deep subsurface operational monitoring results to reservoir and CO₂ injection models designed to predict the behavior of injected CO₂ within the storage complex. Project developers could also deploy monitoring devices to detect leakage of CO₂ at the surface, in which a comparison would be made between surface monitoring data and natural variations in CO₂ levels from organic matter and vegetation in the local environment. Other monitoring tools could also provide information on site performance indicators, the location and size of the CO₂ plume, environmental receptors, and other factors.

Examples of conduits for CO₂ leaks to the atmosphere include CO₂ injection wells, oil or gas production wells (if applicable), monitoring wells, and abandoned wells. CO₂ could also escape the geologic containment complex through faults and fissures. However, for properly selected, operated, and closed CO₂ storage operations, the ACR methodology states (Blue Strategies, 2012) that fugitive CO₂ emissions from the geologic reservoir to the atmosphere should not occur. For a CO₂ storage site in compliance with its CO₂ injection permit, the ACR methodology assumes that leakage to the atmosphere is not a threat and that the loss of CO₂ can be assumed to be zero if (Blue Strategies, 2012):

- “Conformance monitoring systems” show that the behavior of CO₂ within the injection zone in the storage complex agrees with modeled predictions and the key assumptions in the site permit are confirmed; and/or
- “Assurance monitoring systems” above (and, if appropriate to the site, lateral to) the injection zone in the storage complex do not detect injected CO₂.

The general framework of an MRV plan for geologic sequestration under the ACR methodology will include the following components:

1. Delineation of the AoR. In the context of the ACR protocol, this AoR appears to refer to the areal footprint of the subsurface CO₂ plume.

2. Identification of potential leakage pathways for CO₂ in the monitoring area and the likelihood, magnitude, and timing of CO₂ reaching the atmosphere through these pathways.
3. A strategy for detecting and quantifying any surface leakage of CO₂.
4. A strategy for establishing the expected baseline level of CO₂ at the various monitoring sites.
5. A summary of the considerations used to calculate site specific variables for the mass balance equation.
6. A plan for monitoring the relevant parameters.

To ensure permanence of CO₂ in the subsurface during CO₂-EOR with storage, an MRV framework under the ACR methodology shall include the following components:

- A static geologic model of the injection reservoir.
- Flow simulations of CO₂ injection conducted to a point in time when the CO₂ plume ceases to migrate after injection is stopped to determine the ultimate extent of the CO₂ plume.
- Based on flow simulations results, delineate a two-dimensional “reservoir boundary” that encompasses the areal extent of the CO₂ plume plus some buffer.
- Identify leakage pathways within this reservoir boundary (usually well bores, faults and fractures).
- Remediation of potential leakage pathways, as needed.
- A monitoring strategy to monitor the areal extent of the CO₂ plume to ensure it remains confined within the reservoir boundary.

As discussed in the ACR methodology, the Interstate Oil and Gas Compact Commission (IOGCC) Task Force on Carbon Capture and Geologic Storage concluded that monitoring and verification of CCS projects would be accomplished best in the subsurface, given the uncertainties and changing technologies of surface monitoring techniques. Their Model Rules and Regulations for CCS projects focus primarily on subsurface monitoring of the geologic storage reservoir and overlying formations through the use of observation wells. The IOGCC Task Force believes that early leak detection in the subsurface of any CO₂ would be the best mechanism to protect public health and safety and the environment and offer sufficient time to address the cause of that leakage. As an example, early detection in the subsurface would allow for the drilling of wells to remediate leakage by producing or capturing leaked CO₂ and re-injecting that CO₂ back into storage. Rather than being overly prescriptive, the IOGCC Task Force has recommended that the Model Rules and Regulations require the operator to submit a comprehensive monitoring plan that is tailored to the specific characteristics of the site.

Regarding EOR, the ACR methodology provides details on how and where to monitor, for three project phases: baseline, operation, and post-injection. Only post-injection includes CO₂ plume and pressure-front tracking.

The uncertainty in detection and assessment of leakage from the subsurface to the atmosphere is dependent on the design and implementation of the site-specific MRV plan. For EOR sites, the geologic storage site is considered well characterized and modeled. The development of a site-specific MRV plan that identifies possible leakage pathways and utilizes a proper set of

monitoring tools to provide assurance of containment and to detect leakage should it occur is critical. There is a wealth of oil and gas industry experience in the design and implementation of proper monitoring tools, many of which are currently being utilized to meet state regulations. Based on this, the ACR methodology states that the uncertainty in detection and measurement of leakage is considered to be low for EOR sites.

Other Frameworks not Included in Tables 1 and 2

United Nations Framework Convention on Climate Change (UNFCCC)

The United Nations Framework Convention on Climate Change (UNFCCC) adopted CCS as part of Clean Development Mechanism (CDM) activities in Durban, South Africa, in December 2011 (UNFCCC, 2011; Dixon et al., 2013). Because of the perceived uncertain nature of long-term storage provided by GCS, net reversal of storage is noted as a possibility, as are the appropriate time frames for credits and monitoring. Specifically, two phases of verification are established, the first being when credits are earned (while CO₂ is being injected and stored), and the second after credits stop being earned (while injection is no longer occurring) and before monitoring stops. Seepage during crediting is deducted from credits. Seepage after end of crediting is quantified, reported, and addressed using the reserve account.

Forbes and Ziegler (2010) provide numerous recommendations for CCS monitoring under UNFCCC mechanisms. Regarding MMV, they recommend site-specific monitoring plans covering CO₂ and displaced fluids, and a criterion for when monitoring can end. In short, they propose that the operator must demonstrate to the satisfaction of the cognizant regulator that it is safe to end monitoring. Forbes and Ziegler (2010) list specific surface monitoring approaches including groundwater sampling, CO₂ monitoring, tracers, LIDAR, and eddy covariance flux monitoring.

International Organization for Standardization (ISO)

ISO has developed a very general standard for GHG emission quantification and reporting called ISO 14064-2:2006, 2009. Because there is a fee for obtaining the ISO documentation, we opted to review the Indian government's GHG inventory and reduction reporting program which purports to be identical to the ISO 14064-2 standard (Bureau of Indian Standards, 2006). This ISO document provides a very high-level overview of how to go about quantifying, monitoring, reporting, and validating GHG inventories and projects with nothing specifically related to CCS. The ISO document assumes that all sources of emissions are considered, requires baseline data against which to judge reductions, suggests conservatism to handle uncertainty, and includes the need to consider risk of reversal. The ISO document requires a high-level plan describing the whole project, but does not provide additional detail of monitoring for surface leakage. The strength of the ISO document is in the clear definition of terms and guidelines for GHG reporting processes and procedures. However, the high-level analysis contained in the document provides no detail about the specific challenges of MVA related to CCS, or a description of how to go about accomplishing any of the required steps. As such, it has little to contribute to the question of what should be included in an MVA protocol for California's Cap-and-Trade and LCFS programs.

Table 1. Major monitoring elements of MVA for various GHG reduction protocols.

	<u>US EPA 40 CFR 98 Subpart RR MRV</u>	<u>US EPA 40 CFR 98 Subpart UU MRV</u>	<u>EU Emissions Trading Scheme</u>	<u>PEW C2ES</u>	<u>ACR</u>
Major monitoring element	Applies to injection of CO ₂ for geologic sequestration.	Applies to any injection of CO ₂ (e.g., for enhanced recovery).	Applies to any GHG reduction project seeking credit under the EU-ETS.	Applies to CCS projects while maintaining consistency with ISO 14064-2:2006.	Accounting methodology is based on accounting framework developed by PEW C2ES. ACR focuses on oil and gas reservoirs.
Scope	Monitoring applies only to CO ₂ received and injected at the injection site-no capture or transportation components are included.	Monitoring applies only to CO ₂ received at the injection site-no capture or transportation components are included.	Comprehensive monitoring of all emissions from all sources.	Reductions are quantified relative to baseline emissions, and all emission sources are considered. Standards-based or Projection-based methods can be used.	Reductions are quantified relative to baseline emissions, and all emission sources are considered. Standards-based or Projection-based methods can be used.
Plan requirements	An MRV plan is required. The Class VI site characterization and AoR modeling predictions can provide the basis for the Subpart RR MRV, which needs to specify how monitoring will detect and quantify surface leakage.	No explicit mention of MRV plan for UU. The only reporting is for quantity received, source, and concentration.	Required.	CO ₂ storage monitoring plan needs to be incorporated into the overall project monitoring plan. Strives to be consistent with ISO 14064-2: 2006 while focusing on CCS.	MRV plan needs to be developed for geologic sequestration, with several elements (AoR, characterization of pathways, strategy for leakage monitoring and baseline data collection, etc.).
Approval	US EPA, which also may revise the plan and issue the final MRV plan.	US EPA.	Competent authority.	See note 1.	Unclear. Also mentions a third party verifier.
Updating	See note 1.	See note 1.	Compared to modeling, with appropriate updates to both.	See note 1.	Annually.
Deviating from plan	See note 1.	See note 1.	Approval of plan modification by competent authority.	See note 1.	See note 2.
Reporting frequency	Annual monitoring report.	Annual report covering CO ₂ received in terms of quantity, source, and concentration.	Annually or more frequently.	See note 1.	Annually.
Discount of allowances for uncertainty in emission detection	See note 2.	See note 2.	de facto in that reported emissions are calculated to be higher if emission quantification is not within 7.5% uncertainty.	A percentage of all tons credited are discounted according to likelihood of a reversal-not uncertainty in detection-over a set period of time.	No mention of uncertainty discount. Discussion of uncertainty in Section 8 considers all uncertainties to be low.
Reporting threshold	None (i.e., any CO ₂ injected must be reported). One exception is short-duration tests to assess local geologic conditions prior to commercial scale injection. Operator is still subject to Subpart UU regulations.	None (i.e., reporting must be done if any CO ₂ is received for injection).	See note 2.	See note 2.	See note 2.
Notes	1) not specified, but it is implicit that EPA-agreement is required. 2) not specified.	1) not specified, but it is implicit that EPA-agreement is required. 2) not specified.	2) not specified.	1) not specified, implicitly defers to applicable GHG program. 2) not specified.	1) not specified, implicitly defers to applicable GHG program. 2) not specified.

Table 2. Details of monitoring elements of MVA for various GHG reduction protocols.

	<u>US EPA 40 CFR 98 Subpart RR MRV</u>	<u>US EPA 40 CFR 98 Subpart UU MRV</u>	<u>EU Emissions Trading Scheme</u>	<u>PEW C2ES</u>	<u>ACR</u>
Details of monitoring element	Applies to injection of CO ₂ for geologic sequestration.	Applies to any injection of CO ₂ (e.g., for enhanced recovery).	Applies to any GHG reduction project seeking credit under the EU ETS.	Applies to CCS projects while maintaining consistency with ISO 14064-2:2006.	Accounting methodology is based on accounting framework developed by PEW-C2ES.
Unit of measure	Metric tons (tonne, or t) Volume conversion to use 60° F and 1 atmosphere as STP.	Metric tons (tonne, or t) Volume conversion to use 60° F and 1 atmosphere as STP.	Metric tons (tonne, or t)	CO ₂ e (tonnes CO ₂ x global warming potential).	CO ₂ e (tonnes CO ₂ x global warming potential)
Emissions from capture	No	No	From combustion and transfer at the capture facility.	Direct and indirect (Scope 1 and Scope 2 emissions).	Direct and indirect (Scope 1 and Scope 2 emissions).
Emissions from transport	See note 2. Pipeline and containerized transport are covered in terms of reporting mass of CO ₂ received.	See note 2. Pipeline and containerized transport are covered in terms of reporting mass of CO ₂ received.	Mass balance approach.	Direct and indirect (Scope 1 and Scope 2 emissions) only for pipelines.	Direct and indirect (Scope 1 and Scope 2 emissions) only for pipelines.
Emissions from injection	See note 2. Operational emissions not specifically related to CO ₂ injection do not have to be reported under Subpart RR.	No	Fugitive emission fraction calculated using industry best practices.	Direct and indirect (Scope 1 and Scope 2 emissions).	Direct and indirect (Scope 1 and Scope 2 emissions).
Emissions from storage complex (not leakage-related)	Reporting of venting and equipment leakage required to the “extent they are considered part of the G(C)S mass balance.”	No	See note 2.	See note 2.	Considers emissions from energy use for injection and facilities, venting, fugitive releases, produced or transferred CO ₂ from EOR.
Emission from leakage from storage complex	Surface leakage pathways must be identified, and annual report must include discussion of monitoring and detecting “the surface leakages” and uncertainties in calculating the amount emitted. Mass lost by surface leakage must be estimated as per MRV plan.	No	Leakage emissions amounts must be quantified with less than or equal to 7.5% uncertainty. Uncertainty above this amount must be reported. Emissions refer to CO ₂ entering the atmosphere.	Site-specific, and fit-for-purpose consistent with EPA’s Subpart RR GHG MRV program.	Site-specific, and fit-for-purpose. Assumes monitoring and verification would be best accomplished in the subsurface (due to uncertainties in surface monitoring). Suggests monitoring of reservoir and early leak detection in overlying formations.
Leakage (sensu movement of CO ₂)	Insofar as leakage pathways are mentioned, there is implicit reference to subsurface leakage (migration out of the storage complex).	No	Other than the reference to migration (see below), leakage monitoring is not explicitly mentioned. Leakage refers to transport out of storage complex, but not into atmosphere.	Some references included in Section 12 cover leakage and migration of CO ₂ (i.e., within and out of the storage complex).	Some references included in Section 12 cover leakage and migration of CO ₂ (i.e., within and out of the storage complex).
Migration	No	No	The plan must include technologies capable of detecting presence, location and migration paths of CO ₂ in subsurface and at surface (item j, Annex II)	Some references included in Section 12 cover leakage and migration of CO ₂ (i.e., within and out of the storage complex).	Some references included in Section 12 cover leakage and migration of CO ₂ (i.e., within and out of the storage complex).
Specific monitoring methods described	No	No	No	Best practices where they exist, and fit-for-purpose where novel (e.g., emissions from GCS sites).	Mentions <i>IOGCC Model Rules and Regulations for CCS Projects</i> . For CO ₂ -EOR, more specific methods are described.
Monitoring CO ₂ produced (e.g., in enhanced recovery)	CO ₂ concentration in produced fluid must be monitored on a quarterly basis.	Only the amount of CO ₂ received annually must be reported.	See note 2.	See note 2.	Monitoring in required and includes CO ₂ in produced water (annually), CO ₂ in produced hydrocarbon

	<u>US EPA 40 CFR 98 Subpart RR MRV</u>	<u>US EPA 40 CFR 98 Subpart UU MRV</u>	<u>EU Emissions Trading Scheme</u>	<u>PEW C2ES</u>	<u>ACR</u>
					(annually), CO ₂ transferred (monthly).
Relation to enhanced recovery	Subpart RR applies specifically to CO ₂ injection for sequestration.	Subpart UU applies specifically to CO ₂ injection for any other reason than sequestration (e.g., for enhanced recovery).	Directive applies only if CO ₂ is being stored.	Enhanced recovery is specifically mentioned in the context of producing (P) and non-producing (NP) sites.	Enhanced recovery is specifically mentioned. Monitoring requirements for EOR are quite detailed for the subsurface, but not for surface. Not clear what the specifications are based upon.
Composition of injection stream	CO ₂ concentration must be measured on a quarterly basis.	CO ₂ concentration must be measured on a quarterly basis. The source of CO ₂ must also be reported.	Must be measured and reported on frequency determined by competent authority less than or equal to annually.	Monitored monthly.	Monitored monthly.
Approach to dealing with missing data	Estimate missing data based on last-measured values.	Estimate missing data based on last-measured values.	See note 2.	See note 2.	See note 2.
Detection of emissions	Referred to only in description of annual report contents.	See note 2.	No methods proposed.	Project should establish CO ₂ detection thresholds to have confidence in ability to confirm effectiveness of storage.	Project should establish CO ₂ detection thresholds to have confidence in ability to confirm effectiveness of storage.
Emission detection limit	See note 2.	Not applicable, as only injection is considered.	None, except that measured emissions must be quantified to less than or equal to 7.5% uncertainty.	Project should establish CO ₂ detection thresholds to have confidence in ability to confirm effectiveness of storage.	Project should establish CO ₂ detection thresholds to have confidence in ability to confirm effectiveness of storage.
Uncertainty in quantifying emissions	See note 2.	Not applicable, as only injection is considered.	Multiplier formula is provided if uncertainty is determined to be greater than 7.5%.	Mentioned with respect to reversals.	Considered low.
Tiers	CO ₂ injection only is Tier 1; GCS is Tier 2.	CO ₂ injection only is Tier 1; GCS is Tier 2.	Tier 1 has highest uncertainty; Higher tier numbers are more stringent with regard to uncertainty. Tiers refer to set requirements for various quantities (e.g., calculation factors).	See note 2.	See note 2.
Additionality	Not applicable, as this is a reporting protocol only.	Not applicable, as this is a reporting protocol only.	Considered insofar as the EU ETS recognizes Certified Emission Reductions (CERs) of the UNFCC CDM.	Program administrators may require an assessment of additionality (e.g., based on role of value of offset credit in making the project happen).	See note 2.
Leakage (sensu displacement of emissions)	Not applicable, as this is a reporting protocol only.	Not applicable, as this is a reporting protocol only.	Free allowances are allocated according to risk of leakage in the subject industry based on an EU-agreed list that is updated every five years.	Project boundary intentionally drawn broadly to avoid unaccounted emissions.	Project boundary intentionally drawn broadly to avoid unaccounted emissions.
Reversal of emission reduction	Not applicable, as this is a reporting protocol only.	Not applicable, as this is a reporting protocol only.	See note 2.	A percentage of all tons credited are discounted according to likelihood of a reversal over a set period of	No discount.

	<u>US EPA 40 CFR 98 Subpart RR MRV</u>	<u>US EPA 40 CFR 98 Subpart UU MRV</u>	<u>EU Emissions Trading Scheme</u>	<u>PEW C2ES</u>	<u>ACR</u>
				time.	
Post-injection period for project continuance, monitoring and verification	Reporting to continue until Administrator approves closure.	See note 2.	See note 2.	See note 2.	Minimum post-injection period is 5 years. To be extended in 2-year increments if monitoring is not conforming with model predictions.
Notes	1) not specified, but it is implicit that EPA-agreement is required 2) not specified	1) not specified, but it is implicit that EPA-agreement is required 2) not specified	2) not specified	1) not specified, implicitly defers to applicable GHG program 2) not specified	1) not specified, implicitly defers to applicable GHG program 2) not specified

4. DISCUSSION

In order to evaluate the entire CCS chain in terms of benefit to the environment resulting from GHG emissions reductions, the boundaries of the system need to be carefully drawn. In this report, we focus only on the geologic storage part of the CCS process. Additional and separate MVA plans will need to be developed to cover all direct and indirect emissions, additionality,⁸ and leakage (in the sense of decreased emissions within California that result in increased emissions outside of California). The discussion and recommendations for MVA requirements in this section apply only to the surface leakage component of potential GHG emissions arising from CCS. These emissions may comprise GHGs other than CO₂.

While the existing GHG reduction protocols provide an excellent foundation upon which to build MVA requirements, none of the monitoring protocols we reviewed should be used as-is for the purposes of specifying surface leakage MVA requirements for California. On the other hand, surface leakage MVA requirements for California should be consistent with all of the U.S. EPA requirements (e.g., under Class VI, Class II, and Subparts UU and RR), as appropriate for the activity of interest. Below, we review the policy objectives of surface leakage MVA in California, and recommend how a California surface leakage MVA protocol should handle all of the major and detailed elements of GHG MVA (presented in Tables 1 and 2, respectively) for surface leakage.

The key to informed decision making regarding the minimization of environmental impacts associated with GHG emission reduction strategies is risk assessment. In short, decision makers need to be able to examine the risks and benefits of given strategies for GHG emission reductions. In the context of GCS and the reduction of GHG emissions, one of the main issues is the risk of leakage of CO₂ (impact of leakage multiplied by likelihood of leakage) from the storage reservoir into the atmosphere. In order to develop useful and defensible risk assessments, it is a policy objective in California to assure that an operator's surface leakage MVA plan will inform and validate the leakage risk assessment(s) for potential GCS sites. Given the site-specific nature of the geologic conditions at any GCS site, the surface leakage MVA plan also needs to specify spatial and temporal monitoring approaches to assure that the objective of reducing net GHG emissions is being achieved, and to quantify the amount of CO₂ that is permanently stored. Monitoring of subsurface processes is challenging and subject to uncertainty depending on the approaches used, the geology and the hydrology of the site, and many other factors. Given this reality, California policy requires a quantitative estimate of the uncertainty in surface leakage.

As for the GCS opportunities in California, the earliest projects are very likely to involve CO₂-EOR in existing oil fields (e.g., in the southern San Joaquin Valley and Los Angeles Basins). Another potential sink for CO₂ is in depleted gas reservoirs, with or without EGR, in the Sacramento Basin. Deep saline formations in California's Central Valley provide another GCS target which may also be of interest to industry depending on future economic factors. Off-shore GCS has not been discussed widely in California, and therefore is not considered further in this report.

⁸ Emission reductions must be additional to what would have occurred in the absence of the project in a conservative business-as-usual scenario.

Given the California-specific policy and GCS opportunities discussed above, we can recommend some specific elements of a California surface leakage MVA protocol. First of all, we recognize that California is a large state with its own regulatory agency (CARB) implementing its own Cap-and-Trade and LCFS programs. As such, CARB can and should serve as the cognizant agency in all matters regarding reducing GHG emissions in the State. Furthermore, CARB should work with other relevant permitting agencies, as appropriate, to evaluate surface leakage MVA plans. This having been said, CARB's requirements laid out in the surface leakage MVA protocol should all be consistent and never weaker than U.S. EPA's requirements. There should be very close integration of U.S. EPA's existing UIC and Subparts RR and UU requirements with CARB's requirements. Operators carrying out GCS in the State should find that in complying with CARB's MVA rules, they are simultaneously complying with U.S. EPA's GCS rules (e.g., Class II, Class VI, and Subparts UU and RR, as appropriate).

Presented in Tables 3 and 4 are recommendations for California-specific attributes of the surface leakage MVA protocol and corresponding reporting for both the major elements (Table 3) and the detailed elements (Table 4). We note first in Table 3 the inclusion of CH₄ as a target of monitoring. Although there is a tendency to focus on CO₂ leakage monitoring because CO₂ is the GHG being captured and sequestered, it is important to note that CH₄ is also a potent GHG, the emissions of which need to be avoided. In certain CO₂ injection scenarios, particularly those involving CO₂-EOR or EGR, there is the potential for surface leakage of geologic CH₄. It is important to make a distinction between geologic CH₄ (e.g., originating in a deep formation, which should be considered part of surface leakage) and shallow biogenic CH₄ (e.g., originating in the soil or a surface wetland, which should not be part of the surface leakage MVA protocol). In the case that CH₄ emissions above background are detected, the origin of the CH₄ should be determined by best-practice approaches, such as through carbon-source attribution assessment using isotopic (e.g., Oldenburg et al., 2003; Korre et al., 2012) and/or gas-concentration ratio-based methods (e.g., Romanak et al., 2012). In the case that a wellhead leaks geologic CH₄ during CO₂-EOR, the benefit of GCS could be partially negated. To avoid this pitfall, we recommend that CO₂ and CH₄ surface leakage be monitored and reported under the surface leakage MVA plan for CO₂ injection into oil or gas reservoirs. Implicit in all concepts of monitoring is the need to establish agreed-upon monitoring areas (e.g., consistent with U.S. EPA's MMA and AMA).

Second, we note that updating and changing (i.e., deviating from the originally approved plan) MVA activities will be inevitable in GCS projects over long periods of time. Therefore, we recommend that periodic review, updating, and re-approval of the surface leakage MVA plan be sanctioned by CARB. Reporting frequency is recommended to be quarterly in the early stages of projects (first five years) and with approval from CARB, annually after that if operations are going well (i.e., with no evidence of unexpected reservoir or wellbore leakage behavior). Finally, allowing for discounting at CARB's discretion could provide a mechanism to address uncertainty related to monitoring and the permanence of stored CO₂, while also allowing operators flexibility in monitoring resource allocation. We believe there will be a natural or de facto lower bound in reporting threshold controlled by the limitations of monitoring technology and the challenging environments in which monitoring must take place, and we suggest that, at least initially until GCS becomes more widespread, no lower-bound reporting threshold be established.

Table 3. Recommendations for major elements of the surface leakage MVA plan for California.

	Recommendation for California	Notes
Major monitoring element	Applicable to injection of CO ₂ for enhanced recovery and geologic sequestration	
Scope	CO ₂ and CH ₄ emissions (i.e., surface leakage from the storage reservoir). Capture and transportation emissions should be included in a separate monitoring plan.	CH ₄ is also an important GHG. Geologic emissions (e.g., surface leakage of CH ₄ through wells) should be monitored and accounted for especially in CO ₂ -EOR and CO ₂ -EGR projects.
Plan	Required.	Surface Leakage MVA Plan.
Approval	CARB to serve as cognizant authority on surface emissions, approval of MVA plan to occur with additional review and approval by other relevant permitting agencies	CARB's requirements can more strict but should also be entirely consistent with US EPA requirements
Updating	Allowed with approval by CARB.	
Deviating from plan	Allowed with approval by CARB.	
Reporting frequency	Quarterly reporting for first five years, annual reporting after that including for a period consistent with, or longer than, the U.S. EPA PISC period.	Additional reporting may be required under EPA UIC Class VI requirements. PISC time frames should at all times be consistent or longer than monitoring prescribed by the U.S. EPA
Discount of allowances for uncertainty in emission detection	With approval by CARB, uncertainty in emission detection may be allowable if compensated by discount in certified CO ₂ storage.	
Reporting threshold	None. Any CO ₂ or CH ₄ detected as emission must be reported.	

Table 4 presents the recommendations for California on each of the details of the protocol elements presented in Table 2 for existing protocols. Regarding emissions from capture and transport operations, we again mention that a separate MVA plan should be developed for surface emissions related to these operations (see recommendations for future work in the *Conclusions* section). The reason for this separation in MVA plan development is that monitoring for surface leakage (i.e., emission leakage originating from failure of the natural containment of the cap rock and/or the containment of the well completion) is a much different endeavor than typical mass-balance/flow-meter-based monitoring carried out for engineered systems at the ground surface. Surface leakage MVA requires innovative applications and deployments of existing and new technologies (e.g., LIDAR and open-path laser systems). We further believe that monitoring CCS GHG emissions broadly (e.g., emissions from the energy penalty from capture, from pipeline transportation), are much more well-established and can be adopted as-is from existing best-practice experience. On the other hand, surface leakage MVA expertise is still evolving and we expect that a surface leakage MVA plan may require repeated revisions during the lifetime of a project and as experience is gained in the performance of GCS systems.

As for items regarding emissions from leakage from the storage complex, leakage in the sense of movement of CO₂ and migration are the main objectives of monitoring under any surface leakage MVA plan. Quantifying surface leakage will require surface monitoring approaches, (e.g., open-path laser systems that can detect CO₂ and CH₄ concentration anomalies above background levels). Following attribution assessment that determines the presence of significant deep-source (geologic as opposed to shallow biogenic) carbon is present in the anomalous CO₂ and CH₄ signals (e.g., Oldenburg et al., 2003; Korre et al., 2012; Romanak et al., 2012), these anomalous concentration signals can then be used to target areas for more detailed monitoring to estimate emission fluxes. Surface leakage MVA plans need to specify strategies for quantitative surface monitoring with sufficient detail such that CARB may confidently certify the

effectiveness of the approach. In addition to surface monitoring, the plan should include monitoring of the injection and migration processes in the reservoir to a degree that can serve to verify that storage is occurring, and provide information on unexpected or potentially problematic movement of CO₂ within or out of the storage zone. If CO₂ is detected to be moving out of the storage zone, this information will be critical as an early warning of possible future surface leakage, and provide information critical to revising the storage strategy and the surface leakage MVA plan.

The degree of specification required for monitoring approaches under an MVA plan is discussed in Table 4. The section of the surface leakage MVA plan describing monitoring approaches used needs to be sufficiently detailed that an expert in GCS monitoring can understand the monitoring rationale and approve of its intended effectiveness. Some elements of the monitoring approach that should be discussed include, but are not limited to, the following:

1. Overall approach (i.e., measurement-based, or measurement and calculation-based);
2. Baseline monitoring including type and duration;
3. Properties to be monitored (i.e., pressure, temperature, concentration, seismic velocity, rock deformation, etc.);
4. Technology or approach to be used, including integration of technologies;
5. Region(s) to monitor (e.g., injection zone, above-zone, shallow subsurface, or surface/atmospheric);
6. Frequency of measurement;
7. Spatial coverage, both region and intensity (e.g., number of points per area of ground);
8. Schedule of monitoring, including a phased approaches for different project phases;
9. Attribution monitoring, to discriminate shallow biogenic from geologic carbon in CO₂ and CH₄ (e.g., Oldenburg et al., 2003; Korre et al., 2012; Romanak et al., 2012);
10. Proxy and/or companion gas monitoring (e.g., Klusman, 2003; Trottier et al., 2009); and
11. Use of gas or groundwater tracers.

Insofar as the U.S. EPA may also specify surface air or soil-gas monitoring as part of the UIC approval process, the surface leakage MVA plans for California also need to be consistent with these monitoring requirements.

CARB must know whether the CO₂ injection is primarily for EOR or EGR, or whether it is primarily for GCS. There are at least two reasons this difference is important. First, the U.S. EPA considers CO₂-EOR under its Class II UIC program, and GCS under the Class VI program, with substantial differences in requirements for each project type. Second, the actual processes undertaken in the field for these project types are also very different. For example, in CO₂-EOR, CO₂ is supplied at a decreasing rate over time as more and more CO₂ is recycled upon recovery with produced oil. In GCS, CO₂ is supplied and injected continuously with no relevancy of a recycling concept. In EOR or EGR, oil and/or natural gas are produced along with dissolved or free-phase CO₂ that must be separated on site, recompressed and re-injected. This additional

processing gives rise to additional possibilities for CO₂ and/or CH₄ emissions. Finally, in an EOR or EGR system, the pressure rise in the reservoir may not be as large as in a pure GCS system because oil and/or natural gas are being continuously produced. These differences are widely recognized, and the U.S. EPA is currently developing rules to handle transitioning of wells from CO₂-EOR wells to GCS wells (U.S. EPA, 2013d).

Table 4. Recommendations for details of elements of the surface leakage MVA plan for California.

	Recommendation for California	Notes
Details of monitoring element	Applicable to injection of CO ₂ for enhanced recovery and GCS	Elements of the surface leakage MVA plan.
Unit of measure	Metric tons (tonne, or t).	Volume conversion to use 60° F and 1 atmosphere as standard temperature and pressure (STP).
Emissions from capture	Not included.	To be included in a separate MVA plan.
Emissions from transport	Not included.	To be included in a separate MVA plan that includes emissions from pipeline and containerized transport within the footprint of the injection project.
Emissions from injection	Operational emissions directly related to CO ₂ injection (e.g., wellhead and/or well casing leaks) must be monitored and reported.	No lower-bound reporting threshold (i.e., all CO ₂ and CH ₄ emissions must be reported).
Emissions from storage complex (not related to leakage)	Emissions from energy use related to storage must be reported but not under the surface leakage MVA plan.	The rationale for this separation is that monitoring for surface leakage is a much different endeavor than typical mass-balance/flow-meter-based monitoring carried out for engineered systems at the ground surface. However, we note that the separate MVA plans should be incorporated into the larger QM for emission reductions attributed to the project.
Emission from leakage from storage complex	Potential surface leakage pathways must be identified, and reporting must include a discussion of approaches for monitoring and detecting surface leakage. Uncertainties in estimating the amount emitted must also be reported. Mass lost by surface leakage must be estimated by approach in MVA plan.	
Leakage (sensu movement of CO ₂)	Discussion of CO ₂ trapping and/or migration within (or out of) the storage zone should be included in each report.	
Migration	See above.	
Specific monitoring methods described	The specific monitoring technology and deployment approach need to be specified, with the understanding that some flexibility in the actual deployment depending on site conditions may be permitted.	MVA plan needs to be sufficiently detailed such that an expert can understand and approve of the approach, its expected results, and associated uncertainty.
Monitoring CO ₂ produced (e.g., in enhanced recovery)	CO ₂ concentration in produced fluid to be reported quarterly.	Required by U.S. EPA Subpart RR.
Relation to enhanced recovery	Main purpose of CO ₂ injection must be stated (i.e., CO ₂ -EOR or GCS, etc.) and updated over time if applicable.	May require transitional permit by U.S. EPA.
Composition of injection stream	CO ₂ concentration measured, and source noted, quarterly.	Required by U.S. EPA Subparts RR and UU.
Approach to dealing with missing data	Specified in plan and approved by CARB.	
Detection of emissions	Detection limits estimated in plan approved by CARB.	
Emission detection limit	See above.	
Uncertainty in quantifying emissions	Approach to uncertainty estimation in plan approved by CARB.	
Tiers	No tiers in the EU ETS sense, where they referred to degree of uncertainty in calculating parameter values.	
Additionality	Out of scope of surface leakage MVA plan.	
Leakage (sensu displacement of emissions)	Out of scope of surface leakage MVA plan.	
Reversal of emission reduction	Out of scope of surface leakage MVA plan.	Part of overall CARB policy on surface leakage.
Post-injection period for project continuance, monitoring and verification	Annual reporting for a period consistent with, or longer than, the PISC period of the U.S. EPA Class VI or Class II requirements.	

We recommend that the following elements of the MVA plan be specified and approved by CARB: composition of the injection stream, approach to dealing with missing data, detection of emissions, and emission detection limit. The specific approaches to determining these elements will vary depending on the project, but overall the approaches should be based on best practices and/or well-known and accepted approaches. The final detailed element pertains to post-injection monitoring frequency, which should be at least as stringent as the agreed-upon post-injection site care (PISC) monitoring requirements negotiated between the operator and the U.S. EPA.

5. SUMMARY AND CONCLUSIONS

This review and comparison of MVA protocols for CCS from around the world focuses on aspects specific to the geologic storage part of CCS. The purpose of the study was to recommend surface leakage MVA protocols that can be used to develop defensible and practical MVA protocols for California's Cap-and-Trade and LCFS programs. The project was carried out through literature review and analysis.

We found that none of the surface leakage components of existing GHG reduction protocols is completely appropriate for California, but various elements of all of them could be adopted and/or augmented to develop a rigorous, defensible, and practical surface leakage MVA protocol for California. The key requirements of the recommended surface leakage MVA protocol for California are that it informs and validates leakage risk assessment, be specific about the most effective monitoring strategies while still being flexible enough for site-specific conditions, allow quantification of stored CO₂, and offer estimates of uncertainty in the monitored properties. California's surface leakage MVA protocol should be applicable to CO₂-EOR and injection of CO₂ into depleted oil or gas reservoirs with or without enhanced recovery, as well as deep saline storage in order to match the GCS opportunities in California. In addition, the protocol needs to be applicable out-of-state where entities may participate in California's GHG reduction programs under the authority of local permitting agencies presumably with equivalent permitting goals, purposes, and functions.

Our recommendations for California are that: (1) both CO₂ and CH₄ surface leakage should be monitored, especially for injections into oil or gas reservoirs, because CH₄ is also a potent GHG; (2) CARB should be the cognizant authority working together with other agencies to review and approve the surface leakage MVA plan; and (3) CARB may consider the option of allowing operators to receive a discount in certified CO₂ storage for less intensive monitoring, thereby potentially providing a mechanism to address uncertainty related to monitoring and the permanence of stored CO₂ while also allowing operators flexibility in monitoring resource allocation. As for the detailed elements of the surface leakage MVA plan, our main recommendations are that: (i) emissions from all sources not directly related to injection and geologic storage should be monitored and reported under a plan separate from the surface leakage MVA plan; (ii) the primary objective of the surface leakage MVA plan should be to quantify surface leakage of deep-sourced CO₂ and CH₄ and its uncertainty, with application of best-practice and state-of-the-art approaches to monitoring; (iii) effort should be made to monitor CO₂ storage and migration in the subsurface to anticipate surface leakage monitoring needs; (iv) detailed description of specific monitoring technologies and approaches should be specified in the MVA plan; (v) the main purpose of the CO₂ injection project (enhanced recovery or pure GCS) needs to be stated up front; (vi) approaches to dealing with missing data and quantifying

uncertainty need to be described; and (vii) post-injection monitoring should go on for a period consistent with, or longer than, the PISC prescribed by the U.S. EPA.

6. RECOMMENDATIONS FOR FUTURE WORK

Methods for MVA related to emissions from surface infrastructure not directly related to geologic storage (e.g., pipelines, valves, storage tanks, or separators) and from related activities (e.g., energy supplied for pumps, compressors, separation, flaring, or venting) will need to be developed to fully account for GHG emissions in GCS projects, especially those involving enhanced recovery. We recommend an analogous literature review and evaluation to provide a foundation for a California protocol of this part of GHG MVA.

Given the wide interest in California's Cap-and-Trade and LCFS programs, participation by out-of-state entities in California's greenhouse gas reduction programs involving GCS and CO₂-EOR may be common and there will be a need to integrate California's MVA protocols with those of several different states. We recommend a literature review and evaluation to ensure minimal conflicts and maximum consistency with the MVA rules in other states.

There is a need to know what actions to take by project operators if surface leakage is detected. There is a wide range of scenarios of surface leakage (e.g., incipient seepage from wells or surface springs, or well blowouts), and a wide range of time frames for such surface leakage to occur. We recommend that one or more studies be conducted to discuss and evaluate potential responses to leakage events of various types and magnitudes, including reversal of storage in a post-closure time frame following accounting of emission reduction credits.

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ABBREVIATIONS

ACR	American Carbon Registry
AMA	Active Monitoring Area
AoR	Area of Review
CA	Corrective Action
CARB	California Air Resources Board
CAT	Climate Action Team
CCS	Carbon Dioxide (CO ₂) Capture and Storage
CER	Certified Emission Reduction
CDM	Clean Development Mechanism
CFR	Code of Federal Regulations
CO ₂ e	GHG emissions stated in terms of the equivalent climate forcing of CO ₂
EU	European Union
ETS	Emissions Trading Scheme
EGR	Enhanced Gas Recovery
EOR	Enhanced Oil Recovery
ETS	(EU) Emissions Trading System
EU	European Union
GCS	Geologic Carbon Sequestration
GHG	Greenhouse Gas
IEAGHG	International Energy Agency Greenhouse Gas
IOGCC	Interstate Oil and Gas Compact Commission
ISO	International Organization for Standardization
LBNL	Lawrence Berkeley National Laboratory
LCFS	Low-Carbon Fuel Standard
LIDAR	Light Detection And Ranging
MIT	Mechanical Integrity Test

MMA	Maximum Monitoring Area
MMV	Measurement, Monitoring, and Verification
MRV	Monitoring, Reporting, and Verification
MRR	Mandatory Reporting Requirement
MVA	Monitoring, Verification, and Accounting
NP / P	Non-Producing / Producing
P	Pressure (Pa)
PEW-C2ES	Pew Research Center-Center for Climate and Energy Solutions
PISC	Post-Injection Site Care
QA	Quality Assurance
QM	Quantification Methodology
STP	Standard Temperature and Pressure
T	Temperature (°F or °C)
TDS	Total Dissolved Solids
UIC	Underground Injection Control
USDW	Underground Sources of Drinking Water
U.S. EPA	United States Environmental Protection Agency
UNFCCC	United Nations Framework Convention on Climate Change

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