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CARBON DIOXIDE CAPTURE AND STORAGE AND THE UNFCCC

Recommendations for Addressing Technical Issues

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SUMMARY

Achieving cuts in energy-related carbon dioxide (CO_2) emissions is critical to avoiding more than a 1.5 degree Celsius (°C) (2.7 degree Fahrenheit [°F]) rise in global temperatures by 2050 and the irreversible and damaging impacts such a temperature rise would have on people and ecosystems.[1] Meeting this challenge will require the international community to implement a portfolio of clean energy technologies and energy efficiency efforts. Most credible analyses project that among these technologies, carbon dioxide capture and storage (CCS) may need to play a substantial role in achieving the necessary emissions reductions. CCS encompasses a suite of existing and emerging technologies for capture, transport, and storage of CO_2 that together can be used to reduce the greenhouse gas (GHG) emissions from fossil fuel power generation and other industrial sources.

CCS and the UNFCCC

A number of countries—including the United States, China, and 27 members of the European Union (EU)—are putting significant resources into the development of CCS technologies, and four commercial-scale projects are in operation in Norway, Canada, and Algeria. At the international level, the role of CCS in new technology mechanisms under discussion at the ongoing United Nations-led negotiations is not yet clear. In an effort to inform the negotiations, this policy brief provides context, concise analysis, and recommendations to Parties for addressing CCS issues raised to date in the twin track United Nations Framework Convention on Climate Change (UNFCCC) and Kyoto Protocol (KP) processes. These issues include:

- Non-permanence, including long-term permanence;
- Measuring, reporting and verification (MRV);
- Environmental impacts;
- Project activity boundaries;
- International law;
- Liability;
- Safety; and
- Insurance coverage and compensation for damages caused due to seepage or leakage.

In addition, the authors explore a broad range of current and future mechanisms and regulatory frameworks whereby the UNFCCC and national governments can consider CCS technologies. The report does not presuppose the successful implementation of CCS around the world. Nor does it make recommendations on whether CCS should be included in specific existing or future UNFCCC mechanisms (such as the Clean Development Mechanism [CDM] or technology mechanisms) or in countries' climate change mitigation commitments and actions (e.g., Nationally Appropriate Mitigation Actions [NAMAs], etc.). Instead, the report focuses on technical issues, with the aim of helping Parties evaluate a robust strategy for CCS as part of international negotiations and establish CCS best practice criteria for governments and the international process, thereby enhancing transparency and ensuring that CCS deployment is safe and effective.

The analysis draws heavily from the World Resources Institute (WRI) report the *Guidelines for Carbon Dioxide Capture, Transport, and Storage* and draws to a lesser extent from WRI's *Guidelines for Community Engagement in Carbon Dioxide Capture, Transport, and Storage Projects*. The report also benefits from the 2005 Intergovernmental Panel on Climate Change (IPCC)'s *Special Report on Carbon Dioxide Capture and Storage*,[2] the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*' methodology for carbon dioxide transport, injection and geological storage,[3,4] and the UNFCCC Experts'

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Report on CCS, *Implications of the Inclusion of Geological Carbon Dioxide Capture and Storage as CDM Project Activities* (UNFCCC/CCNUCC EB 50).[5]

CCS Defined

The term carbon dioxide capture and storage (CCS) as used in this report describes a multistep process that integrates a chain of technologies for the purpose of limiting GHG emissions. The primary target is CO_2, which is captured by separation from gaseous emissions and then compressed, transported, and finally injected into appropriate subsurface geologic formations for long-term storage. This definition excludes methods that would store CO_2 in the water column or ocean seabed; such practices are widely considered environmentally unacceptable. CO_2 can be captured from the emissions of power plants, cement manufacturers, and other industrial facilities and is typically transported by pipeline to underground storage sites. The underground formations used for geologic storage can include saline formations as well as depleted oil and gas reservoirs. The technologies for each step of the CCS process are already used separately for other industrial purposes and in commercial operations around the world. However, to capture and store CO_2, these various technologies must be tailored and integrated specifically for CCS and applied to commercial-scale CO_2 emission sources. There are currently four operating, commercial-scale, integrated CCS projects—Sleipner and Snøvhit in Norway, Weyburn in Canada, and In Salah in Algeria—and many others are under construction or in the planning stages.

Key Recommendations

This brief provides policy recommendations on how negotiators and others active in UNFCCC and KP discussions could address the key issues raised to date in UNFCCC discussions around CCS: long-term permanence; measurement, monitoring, and verification; environmental impacts; project activity boundaries; international law; liability; safety; and insurance coverage. There are several potential avenues through which the UNFCCC might consider or influence CCS projects and deployment, most of which are not yet in place. These include a new technology mechanism, various "sectoral mechanisms," a registry, and the future form of the CDM of the KP, among others (please see Figure 1 for a comprehensive list). Although there is a great deal of uncertainty in the future form and functions of many, if not all, of these avenues, for non-Annex I Parties it seems that some form of review of internationally supported actions is expected, and for Annex I Parties, accounting rules of some form will emerge. Both are needed to enhance transparency and ambition.

Our analysis concludes that the Parties to the UNFCCC should decide whether and when CCS practices are acceptable in the different mechanisms and approaches. However, where CCS is incorporated, best practice criteria—as outlined in Table 1 below—should be established for each of the issues addressed in this brief. These standards should then be integrated into the various functions that might influence CCS projects and deployment. If the Parties pursue our recommendations, these best practices will need to be negotiated and implemented by an appropriate body. This role could be filled by the Subsidiary Body for Implementation (SBI), the Subsidiary Body for Scientific and Technical Advice (SBSTA), or the proposed Technology Executive Committee. However, we would recommend that regardless of which body assumes leadership, best practice criteria should be established by a panel of independent experts representing different geographic regions and with knowledge in the engineering, geological, legal, social, environmental, and financial aspects of CCS. This group would then report back to the appropriate bodies of the UNFCCC. National governments will also play a vital role in any future CCS projects sited within their borders. This paper's recommendations highlight the importance of national environmental

Box 1 WRI and CCS

This brief is one in a series that the World Resources Institute (WRI) has published on CCS. Our work on this topic is not designed to endorse the deployment of CCS technology, but rather to explore whether and how society might safely, reliably, and effectively demonstrate commercial CCS projects on a broader scale in order to determine whether and how CCS might be part of a comprehensive climate change mitigation strategy.

In 2008, WRI published the Guidelines for Carbon Dioxide Capture, Transport, and Storage (see: http://www.wri.org/publication/ccs-guidelines). This first attempt to develop best practices to responsibly implement CCS projects resulted from a broad stakeholder process comprised of experts from academia, industry, and nongovernmental organizations (NGOs), primarily from the United States. In the fall of 2010, WRI published the Guidelines for Community Engagement in Carbon Dioxide Capture, Transport, and Storage Projects (see: http://www.wri.org/publication/ccs-and-community-engagement), covering key issues for CCS plants in relation to disclosure of information, community engagement in the review and approval of plans, and public participation in general. Other briefs in this series cover CCS development in two critical markets: the EU and China.

Table 1 Summary of Key Recommendations

Issue	Recommendation for Projects Recognized or Reported Under UNFCCC Mechanisms	Recommendation for National Governments
All	Establish best practice criteria with input from a panel of geographically diverse, independent experts with knowledge in the engineering, geological, legal, social, environmental and financial aspects of CCS, representing different geographies.	
Long-term Permanence	• Establish CCS project criteria to ensure that best practices are employed for the following – Criteria for site selection based on geologic characteristics of the site – Operational and long-term monitoring – Risk assessment – Long-term stewardship, including the availability of resources for long-term monitoring	• Establish an environmental regulatory framework that promotes storage security and includes: – Criteria for site selection based on geologic characteristics of the site – Operational and long-term monitoring – Risk assessment – Long-term stewardship
Measuring, Monitoring and Verification (MMV) of CCS Efforts*	• Establish monitoring criteria for CCS projects that ensure a site-specific MMV plan is developed and implemented which: – Covers the area of injected CO_2 and any displaced fluids – Requires data reporting and review – Establishes criteria for determining when monitoring can end	• Establish an environmental regulatory framework for CCS that: – Covers the area of injected CO_2 and any displaced fluids – Requires operators to monitor and report key data and information – Establishes criteria for determining when monitoring can end
Environmental Impacts	• Review environmental impact statement (EIS) documentation and withhold support for projects that have not conducted an EIS analysis.	• Ensure environmental regulatory frameworks provide for: – A compositional analysis of the CO_2 stream, which is then used in the site-specific risk assessment • Conduct a comprehensive EIS analysis for any CCS effort, which includes a risk analysis and public participation.
Project Activity Boundaries	• Develop and agree to criteria that evaluate whether an accurate physical boundary has been established and whether best practices for CCS MMV are being employed for CCS projects.	• Ensure an environmental regulatory framework for CCS that requires a monitoring area and project footprint be established based on site specific data, simulations, and risk assessment. • Establish national methodologies for MMV of CCS projects.
International Law	• Endorse guidelines for risk management developed under the London Protocol.	• Follow the rules and best practices of the London Protocol and OSPAR, where applicable.
Liability	• Develop and agree to procedures for evaluating host country post-closure stewardship mechanisms. • Support projects only where adequate management of liability is evident.	• Develop and agree to clear rules and procedures for managing liability in a CCS project. • Develop and agree to criteria for proving that the CCS project does not endanger human health or the environment, and use these as the basis for transfer of liability and stewardship responsibilities.
Safety	• Review the operator's safety record. • Develop and endorse guidelines for risk assessment, environmental impact statements, permanence, and MMV.	• Apply to CCS projects laws that protect worker safety. • Ensure a regulatory framework that prioritizes human and ecosystem safety.
Insurance Coverage and Compensation for Damages Caused due to Seepage or Leakage	• Require insurance or other financial security mechanism for supported CCS projects. • Require proof of mechanism for covering any long-term damages.	• Require operators to have insurance during operational project phases. • Develop a national trust fund or other mechanism for long-term stewardship.

Note

* The ability to measure, report, and verify (MRV) CO_2 emission reduction activities is a key requirement of any greenhouse gas mitigation approach, including CCS. Individual CCS projects require a similar, site-specific process oftentimes referred to as measuring, monitoring and verification (MMV).

regulatory frameworks that promote deploying CCS only where it can be done safely and ensure that projects are operated responsibly and risks managed over the long term. Governments will also want to report reductions gained through CCS projects, which will require an established set of international reporting frameworks and internationally agreed practices.

The key recommendations resulting from this analysis are provided at the end of each section and summarized in Table 1.

INTRODUCTION

Purpose of document

This publication analyzes a range of issues concerning CCS that have been raised in the UNFCCC negotiations. These issues, which focus mainly on the storage aspects of CCS, are listed below and derived from the KP's latest decision on CCS, during the December 2009 meeting in Copenhagen, Denmark, (Decision 2/CMP.5), and further described in the draft decision of the chair of Subsidiary Body for Technical and Scientific Advice in June 2010 (FCCC/SBSTA/2010/L.11).

- Non-permanence, including long-term permanence
- Measuring, reporting, and verification (MRV)
- Environmental impacts
- Project activity boundaries
- International law
- Liability
- Potential for perverse outcomes
- Safety
- Insurance coverage and compensation for damages caused due to seepage or leakage

The authors explore each issue listed, with the exception of the potential for perverse outcomes, which unlike the other topics addressed, has not been the subject of past WRI CCS publications. Concluding each section, recommendations are provided for delegations and Parties to consider as next steps in the UNFCCC process.

This report describes how the UNFCCC and national governments can address the concerns that have been raised in UNFCCC discussions and develop procedures in UNFCCC mechanisms to promote protection of people and ecosystems where CCS might be deployed. However, the authors do not make judgments on whether CCS should be included in specific UNFCCC mechanisms (e.g., CDM or the proposed Technology Executive Committee).

Potentially relevant structures and functions

Given agreement among the Parties, CCS-related issues could be addressed in various proposed and existing UNFCCC fora, including the technology mechanism, registry, KP mechanisms, any market mechanisms being negotiated under the Long-term Cooperative Action (LCA) track, and accounting for Annex I Parties under either the KP or the LCA (see Figure 1). The UNFCCC structures we present are simply one possible scenario and are used to frame the functions we address. Our recommendations apply to the various functions that could influence CCS deployment, wherever they are implemented.

In the October 2010 meetings in Tianjin, China, the Ad Hoc Working Group on Long-term Cooperative Action (AWG-LCA) developed a draft text on the "development and transfer of technologies" that describes a technology mechanism, specifically the structure and functions of a proposed Technology Executive Committee and associated network.[6] Additional functions have also been elaborated in Chapter IV of the AWG-LCA's negotiating text.[7] Based on these drafts, the executive committee's tentative mandate includes aligning international efforts with in-country policies and deployment strategies, analyzing policy and technical issues, recommending program priorities and eligibility criteria, developing and transferring technologies, and developing best practice guidelines. This analysis's recommendations can inform these proposed functions and highlight some of the concrete actions a Technology Executive Committee could take with respect to a given technology. Specifically, these recommendations can help the committee formulate best practices, national policies, and eligibility criteria that ensure that CCS technology, if deployed, is done so safely and effectively. The committee could also use these recommendations to provide policy guidance and advice on specific issues, for example, MMV, non-permanence, and project activity boundaries, and on the robust environmental regulatory frameworks required to deploy CCS. Establishing such best practices and criteria will allow the executive committee to acknowledge and proactively address the concerns about CCS raised by Parties in the negotiations.

Further, the Climate Technology Centre and Network's proposed functions provide another avenue to address CCS-related issues. The center and network are expected to provide advice, technical support, and capacity building to developing countries to facilitate technology transfer and deployment.

Through these efforts, the center and network could help developing countries establish or expand the robust environmental regulatory frameworks required for CCS deployment. In addition, the center and network could apply this document's recommendations when they develop collaborations; customize tools, policies, and best practices; and provide guidance, technical assistance, and training.

The proposed registry is another structure with possible functions that can be informed by these recommendations. According to the facilitator's reflections from the AWG-LCA's drafting group on enhanced action on mitigation,[8] the registry's functions could include recording and recognizing NAMAs and matching them to international support. Here, there is an opportunity if a Party lists CCS or CCS-ready projects or policies as a NAMA to ensure that actions taken and support given to deploy CCS contain criteria and guidance, which ensure that human health and safety and ecosystems are protected. One possibility is that when matching actions to support, the registry could ensure that appropriate eligibility criteria are established for CCS projects in order to address concerns, such as liability, safety, non-permanence, MRV, environmental impacts, and, notably, the existence of a robust environmental regulatory framework, as detailed in this document's recommendations.

Under the existing KP, these recommendations could be instituted by establishing criteria for including CCS in flexible mechanisms (either currently existing, such as Joint Implementation and the CDM, or a future KP mechanism). This may be implemented by establishing a CCS project methodology that addresses each of the issues analyzed and ensures that projects are evaluated based on criteria that are designed to protect human health and safety while ensuring that reductions are real and additional. For accounting issues in inventories, national communications, or other mechanisms, the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (see Box 3) provides methods to incorporate CCS projects. Additionally, for project-based accounting, criteria could be established that ensure a MMV plan is created to support accurate measurement spanning the full physical project boundary and a system is in place for the data to be reported and reviewed by the appropriate authority.

We suggest that at a minimum, the UNFCCC should decide whether and when CCS practices are acceptable in the different mechanisms and approaches. Where CCS is accepted, best practice criteria should be established for each of the issues outlined in this brief by a diverse group of independent experts. However, this report does not attempt to fully explore the re-

FIGURE 1 A Potential Structure of UNFCCC Functions that Could Influence CCS

UNFCCC Technology Mechanism	• Technology Executive Committee • Climate Technology Centre and Network
Registry	• NAMAs, including potential sectoral mechanisms • Climate financing • MRV
Kyoto Protocol Mechanisms	• CDM • Revised CDM rules
Accounting	• Inventories • National Communications • Annex I accounting rules

spective roles of the UNFCCC and national governments in establishing rules for CCS. For example, there may be tension between the UNFCCC and national regulatory requirements, particularly if a project meets national requirements but is ultimately rejected by the UNFCCC.

The Status of CCS Technology

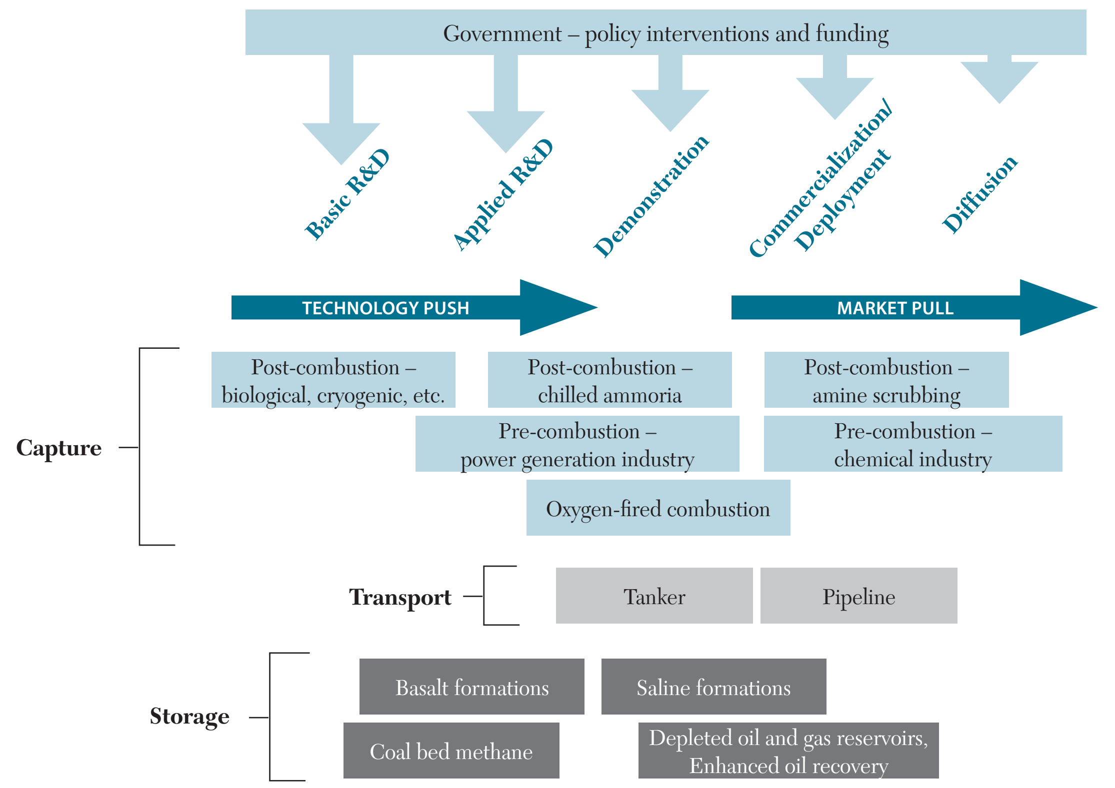
CCS integrates a range of technologies in order to reduce the impact of fossil fuel use and other CO_2 emitting activities. These technologies can be separated into three categories—capture, transport, and storage—each encompassing technologies at various stages of advancement (see Figure 2).[9,10,11,12,13,14]

Capture

The first step in CCS is to capture CO_2, typically from a point source such as a fossil-fueled power plant, biomass combustion, or other industrial sites like ethanol producers, cement or fertilizer manufacturers, and oil and gas refineries.[9,10] Capture processes initially must separate the CO_2 from the flue (exhaust) gases to obtain a nearly pure stream of CO_2.[2] The primary separation and capture approaches are post-combustion, pre-combustion, and oxygen-fired combustion (a.k.a., oxy-fuel). While these technologies exist, further research and development is needed to reduce capital and energy costs and bring such methods to commercial scale, which in this document is defined as a project capturing and storing more than 1 million tonnes of CO_2 annually.[2,9,10] Meanwhile, industrial sources with relatively pure CO_2 emissions are providing early opportunities for low-cost capture demonstrations using each of the pathways described below. In some applications, this captured CO_2 is then utilized for various purposes, such as enhanced oil recovery (EOR) or carbonating beverages. This is sometimes referred to as carbon dioxide capture, utilization, and storage (CCUS).

Modern post-combustion processes typically use a solvent to separate CO_2 from gas mixtures.[9] The most common approach, amine scrubbing, has been used since the 1930s to remove CO_2

FIGURE 2 Range of CCS Technologies and Their Stage of Advancement as of 2010



Note: Innovation chain arrows adapted from E3G/Chatham House.

from natural and hydrogen gas and is utilized at hundreds of plants worldwide.[9,15] As such, it is considered a commercial and mature technology.[9,15] However, impurities, low CO_2 concentrations, and low pressures make capturing CO_2 from post-combustion (power plant) flue gases more challenging.[2] The approach is now operating on limited portions of flue gas from a few power plants, but the technology still needs to be scaled up and improved for widespread adoption by the power sector.[2,9,16,17]

Pre-combustion approaches are typically integrated with plants that gasify and react fuels to produce a mixture of hydrogen gas and CO_2 (e.g., integrated gasification combined cycle [IGCC] plants).[9,11] Higher CO_2 concentrations and pressure make separation easier, and variants of pre-combustion capture technology are already widely used in fertilizer manufacturing and hydrogen gas production.[2] However, there are relatively few full-scale, operational IGCC power plants, and they all lack CCS.[16,18,19] While effective separation of CO_2 with a pre-combustion system has been proven in industrial plants, it has not yet been applied to an operational power plant.[11]

Oxygen-fired combustion generally uses an oxygen-enriched mixture of recycled flue gas, as opposed to air, for combustion.[2,9,11] The resulting flue gas is primarily CO_2 and water, making CO_2 separation and capture easier.[2,9] However, this approach requires oxygen to be separated from the air before combustion, which presents costs but can be achieved with established cryogenic techniques.[2,11] Oxygen-fired combustion has been applied to demonstration-scale (e.g., 30 Megawatt [MW]) power plants, and some larger experiments are expected to be commercially implemented by 2015.[2,9,11,16,20]

Once CO_2 is captured, it is compressed to reduce its volume for easier transportation and to allow for deep underground storage.[2] Gas compression is routine, and current liquefaction processes for petroleum gas could potentially be scaled up and used for CO_2.[2] Although CO_2 compression technologies exist, further research and development may reduce their energy use and cost.[21]

As current capture processes require energy to capture, separate, and compress the CO_2, CCS can affect the emissions source to which it is applied. When CCS is added to a power plant, for example, it is often considered to impose an "energy penalty" because the CCS processes use energy the plant would otherwise be able to provide to customers. Thus, to produce the same amount of energy as a plant without CCS, a CCS-equipped plant must consume more resources, often more fossil fuel and water.[22] Research is underway to reduce the energy and water penalty associated with CCS, with a goal of commercially available CCS technology by 2020.[23]

Transport

Once captured and compressed, CO_2 typically needs to be transported to where it will be stored or otherwise utilized. Options include pipelines, trucks, trains, and tankers. Pipeline transport is typical for compressed gas, although some tankers might also be adapted for carrying liquefied CO_2.[2] Since its beginnings in the 1970s, pipeline transportation of CO_2 has become common, and there are already 6,270 kilometers (km) of CO_2 pipelines operating in the United States.[11,24] While promising, this network would need significant expansion for wide-scale CCS deployment; estimates indicate that 70,000 to 120,000 km of CO_2 pipeline could be needed globally by 2030.[9] Over land, there is also industrial experience transporting CO_2 by rail and truck, but at much smaller scales than would be required.[2] At sea, CO_2 tankers also operate at small scales, but technologies researched and developed for petroleum fuels could be adapted and scaled up.[2]

Storage

Once at an appropriate storage site, CO_2 can be injected into deep subsurface geologic formations for isolation from the atmosphere. Ideal sites are at least 800 to 1000 meters (m) deep (some are 1,500 to 2,000 m deep), have an overlying geologic formation that prevents the CO_2 from escaping, are large enough to store CO_2 over a facility's lifetime, and are permeable enough to allow CO_2 to be injected at reasonable rates.[12] Many ideal subsurface sites contain saltwater (i.e., saline formations).[12] Injected CO_2 can also be reused beneficially, notably for enhanced recovery of oil, coal bed methane and gas.[2,10] To ensure that sites are able to safely and permanently store CO_2, many governments develop site selection criteria, often based on international best practices or other technical guidance.[25] However, a determination that a particular site is suitable requires site-specific investigation, including detailed site assessment, characterization, and modeling.

The technology and feasibility of CO_2 injection and storage has been demonstrated. Research on geologic storage began in the 1990s; and today, integrated CCS projects in Norway (Sleipner and Snøvhit) and Algeria (In Salah) exhibit the feasibility of commercial-scale CO_2 storage in geologic formations.[2,10,11,26,27] Sleipner has been operating since 1996.[28] EOR projects provide another source of industrial CO_2 injection and storage experience, with some projects dating back to the early 1970s.[2,11] For example, the Weyburn project in Canada has demonstrated the CO_2 storage that can be achieved, in conjunction with capture and utilization, in an EOR project.

Storage presents a number of challenges countries are only beginning to address. Notably, long-term stewardship of storage sites requires a regulatory or other competent authority to provide monitoring and potentially remediation of sites over the next several decades and beyond. This stewardship, in turn, requires long-term financing to ensure continued monitoring and maintenance. In addition, the final responsibility for long-term liability is often still undefined.

Integration and scale

Currently, some plants capture CO_2 but do not inject and store it. Other projects inject CO_2 but do not separate it from a flue gas stream. Still others inject CO_2 for EOR but do not necessarily store it. For successful CCS implementation, each piece of the technology chain—capture, transport, and storage—must be integrated into one project and brought to commercial scale. While this scale has been achieved in the gas-processing sector, it is still a major goal for other CO_2-intensive industries such as the power, iron and steel, and cement sectors. After surveying 499 CCS projects and excluding projects that were research-only, completed, cancelled, delayed, or uncategorized, the Global CCS Institute (GCCSI) detailed 213 currently active or planned projects, of which 62 are both integrated and commercial scale.[10] Only a handful of the 62 are operational; and of these, the two aforementioned installations in Norway (Sleipner and Snøvhit) and one in Algeria (In Salah) are the only projects to store CO_2 geologically (as opposed to using it for EOR, which is the case for the Weyburn project in Canada). Although a number of additional commercial-scale projects have been proposed, it is uncertain how many will be built in the near future. Some projects will not meet the necessary technical criteria for safe and secure storage, while others will lack the necessary support from the local community.

Brief History of CCS in the UNFCCC Negotiations

The most extensive discussion of CCS in the UNFCCC negotiations has been under the KP and specifically regarding whether CCS should qualify as a CDM project activity, including the impact such action would have on the overall CDM market. Since November 2005, the issue has been discussed in the Conference of the Parties serving as the Meeting of the Parties to the KP (COP/MOP) and the SBSTA and has been the subject of many technical workshops, experts' and Executive Board reports, and submissions from Parties and NGOs.[29] However, a final decision on CCS's inclusion in the CDM has been repeatedly postponed because of ongoing discussions regarding outstanding issues related to the safety, environmental integrity, temporality, long-term stewardship, and overall performance of the technology (detailed in the next section). While a complete list of the issues identified at each COP meeting can be found in Appendix A, here we focus on the outstanding issues raised in Copenhagen in December 2009, which form the basis of current discussions. At the 32nd meeting of the SBSTA in June 2010, Parties took note of the issues and agreed that they must be addressed and resolved, with consideration expected to resume at the next SBSTA meeting.[30]

Some countries, such as Norway, are already implementing CCS and including it in their national inventories.[31] In the future, other countries may also choose to pursue CCS as a mitigation strategy and want to include it in mitigation commitments, actions, and/or technology mechanisms. Thus, as the end of the first commitment period of the KP draws to a close in 2012, the issues around CCS will need to be more fully addressed so that if CCS is to be included, it can be better integrated and managed in UNFCCC processes. By Parties' addressing these outstanding issues, the UNFCCC should provide certainty and guidance that could help those countries considering and hoping to pursue CCS.

Issue-by-Issue Analysis and Recommendations

For each CCS-related issue below, we attempt to (1) concisely summarize the state of knowledge on the issue from a technical perspective, (2) describe how CCS policies or regulations in other jurisdictions have and/or can address the issue, and (3) make recommendations for next steps that UNFCCC negotiators and governments can take to resolve the issue. As these issues have been addressed in many other technical reports and journal articles, as well as a CDM Executive Board report,[5] we include appendices to direct readers toward key sources of additional information (notably, Appendix B). Our recommendation-oriented approach is designed to ensure that if the UNFCCC decides to recognize CCS projects, it is in a context whereby these concerns can be adequately addressed. The report is organized to mirror the issues as described in KP Decision 2/CMP.5, and as such the issues presented will be:

- Non-permanence, including long-term permanence;
- Measuring, monitoring, and verification (MMV);
- Environmental impacts;

- Project activity boundaries;
- International law;
- Liability;
- Safety; and
- Insurance coverage and compensation for damages caused due to seepage or leakage.

Non-permanence, including long-term permanence

The issue of long-term permanence is primarily a concern about storage security—whether CO_2 stored in the subsurface will in the future leak or seep to the surface. While long-term permanence is mainly considered a technical challenge, the potential consequences of impermanence make it one of the most pressing operational challenges affecting long-term liability, financial considerations such as insurance services and risk premiums, environmental effectiveness, health and safety issues, and intergenerational issues.

In various submissions to the SBSTA, some countries and organizations have expressed concerns about possible leakage while others have expressed confidence that CO_2 can be stored indefinitely. Both groups cite the 2005 IPCC Special Report on CCS, which both (1) acknowledges the potential risk of leakage and uncertainty based on limited industrial-scale CCS projects and (2) emphasizes that such leakage is unlikely *IF* a CCS project is selected carefully, operated responsibly, and monitored over long time frames.[2] As described in WRI's *Guidelines for Carbon Dioxide Capture, Transport, and Storage,* CCS is not a risk-free technology. Each CCS effort will come with a set of site-specific risks, including potential pathways for the CO_2 to escape from the storage reservoir. There are also many sites where CCS will not be possible because they lack the appropriate geology to support secure storage. The WRI Guidelines recommend that storage operators assess the suitability and security of a geologic formation for CO_2 storage based on a site characterization that includes collecting geologic data at the storage site. This can help ensure that only suitable sites are selected.

Following the selection of a suitable storage formation, site-specific operating and monitoring plans should be designed based on the information collected during the site characterization phase. Implementing these plans should help ensure that storage operations are undertaken safely. If risks are identified through a comprehensive site-specific risk assessment, they can often be avoided or managed, and the likelihood that the CO_2 will be contained indefinitely can be increased. In the event of CO_2 leakage, there is also a series of leak mitigation approaches that can be deployed to prevent or reduce further leakage or damage.[25] Moreover, researchers should continue to refine methodologies and develop new tools for site characterization and risk assessment as well as seek a better understanding of the CO_2-trapping mechanisms (detailed in Box 2).

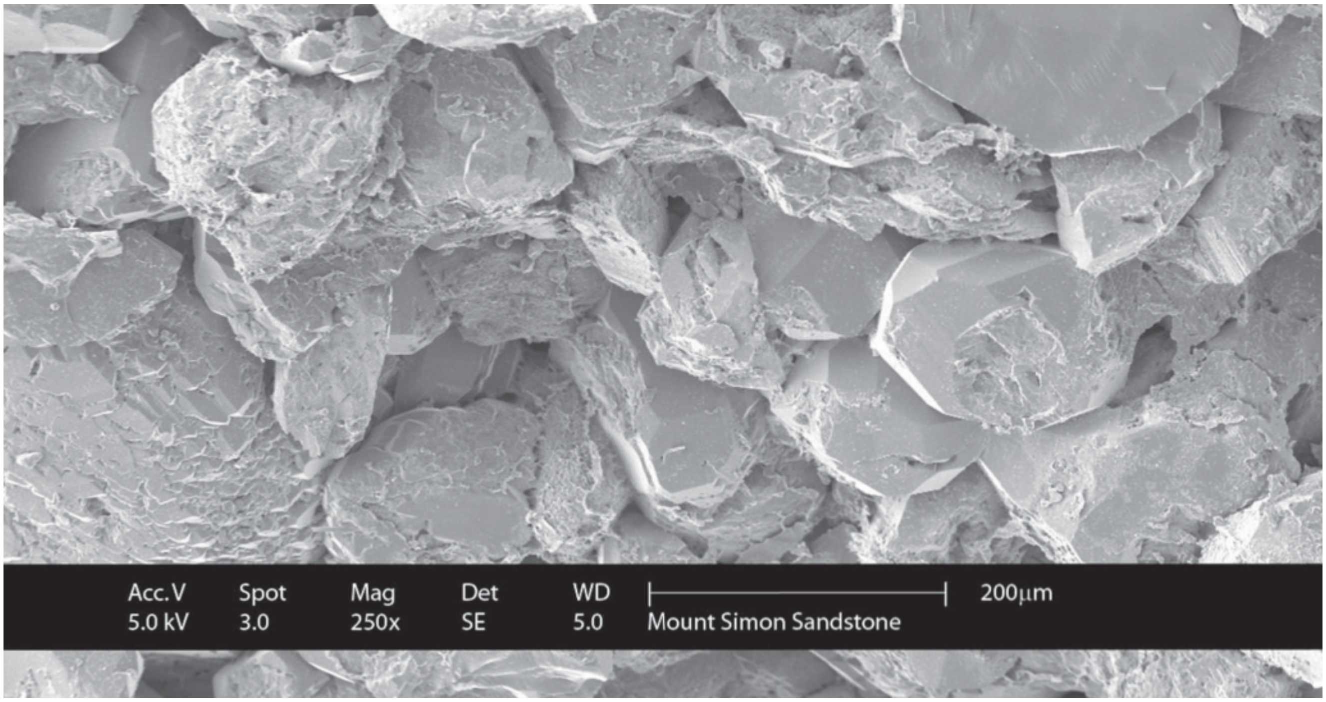
As CO_2 storage relies on site-specific geologic conditions, long-term permanence requires established rules and procedures for ensuring that (1) selected sites have the appropriate geology, (2) the project is constructed and operated responsibly, and (3) importantly, the risks are understood, minimized, and managed. A handful of countries and regions—such as the EU, UK, United States, Australia, and Norway—are in the process of developing or have already developed these regulations, and they have addressed questions of permanence and possible CO_2 leakage or seepage from the subsurface with the following provisions:[32]

Box 2 Geologic Storage of Carbon Dioxide

The assertion made by many scientists that carbon dioxide (CO_2) can be contained in geologic formations rests upon both empirical evidence and geologic investigation.[2,12] Trapping of CO_2 in underground reservoirs already occurs naturally, in what the Intergovernmental Panel on Climate Change (IPCC) describes as a "widespread geological phenomenon" and has a few natural and industrial analogues, including natural gas storage.[2] While geologic storage of CO_2 presents its own unique challenges, it is expected to be successful at carefully selected, appropriately monitored and maintained storage sites.[2]

Over the entire area of storage, the primary trapping mechanism is typically a confining zone (a.k.a., "cap rock"), which is a formation above the storage site that has low permeability and prevents the injected CO_2 from traveling toward the surface.[2,12] When injected below the confining zone, the CO_2 fills pore spaces in the geologic formation, which stores and provides another trap for the CO_2.[2] Sequestered in the subsurface, the CO_2 is then subject to a variety of processes that are expected to make its storage more permanent.[2,12] For example, many proposed storage sites are saline formations, where a brine solution already fills the pores of a geologic formation. The CO_2 is expected to begin dissolving into this solution, a process that increases retention over the course of centuries.[2,12] Then over thousands of years, chemical reactions can take place to store the CO_2 in minerals.[2,12] When injecting into subsurface coal or shale, CO_2 adsorption onto and possibly absorption into the organic matter is theorized to provide long-term immobilization.[2] An appropriate geologic formation has a confining zone, pore space, and typically a combination of processes that are expected to work together to lower the risk of leakage.[2] Other geologies, however, might not be suitable for CO_2 storage; thus potential storage sites require extensive site characterization and monitoring.

FIGURE 3 Geologic Storage Formation Pore Space



Note: This scanning electron micrograph image shows the pore spaces in a geologic storage formation. In these pores inside the rock, the CO_2 would be physically trapped, over time the CO_2 would also mix with the fluid in the formation and dissolve, and over very long timeframes the CO_2 would be expected to mineralize into stable carbonates.

Source: Image courtesy of the Illinois State Geologic Survey.

- criteria for site selection that focus on geologic (both physical and chemical) characteristics;
- requirements for risk assessment and contingency plans; and
- mandatory monitoring and data reporting.

In addition, an integral aspect of any CCS effort is employing the site monitoring results in updating the computational models of CO_2 storage to generate a better risk assessment of possible paths of the injected CO_2 plume. Emerging regulations, such as those in the United States, now codify this iterative improvement, requiring that simulation and risk assessments be updated with monitoring data and repeated during and after injection.

As **UNFCCC negotiators** consider the challenge of long-term permanence for CCS, we recommend that criteria be established and applied to ensure that if the UNFCCC has a future role in approving or supporting projects, any approved projects are selected and operated responsibly, designed to promote secure storage, and monitored over the long term. Such technical criteria should supplement and guide projects, but would not replace the need for national environmental regulatory frameworks. At a minimum, UNFCCC CCS project evaluation criteria should be established, incorporating the most up-to-date technical expertise. To address questions about permanence, the criteria should ensure that a project undergoes the following:

- site selection and characterization based on site-specific geology;
- risk identification, assessment, and management; and
- a long-term monitoring plan.

As **national governments** consider how to address long-term permanence for CCS, we recommend that they consider the lessons learned from the regulatory frameworks in other regions and countries. Governments should establish a national environmental, health, and safety regulatory framework that is designed to promote storage security and includes scientifically sound requirements for site selection, operation, long-term monitoring, risk assessment, and long-term stewardship.[a] Such a framework should include criteria that span the lifetime of a CCS project: project design, operation, and post-closure.

Measuring, monitoring, and verification (MMV)

The ability to measure, report, and verify (MRV) CO_2 emission reduction activities is a key requirement of any GHG mitigation approach, including CCS. Individual CCS projects require a similar, site-specific process often referred to as measuring, monitoring, and verification (MMV). Although there are established protocols for MMV of CCS projects, such as the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, it remains technically impossible to accurately measure the volume of CO_2 after it is stored in the subsurface or to establish a single set of MMV tools that can be applied universally to all CO_2 storage sites. While measurement and monitoring of CO_2 during the capture and transport stages of a CCS effort is not substantially different from other industrial activities, the issue of long time frames for geologic storage requires that a decision be made on when, if ever, it is acceptable to stop monitoring a CO_2 storage facility.

The objective of MMV for a CCS project is to ensure that the injected CO_2 remains stored in the subsurface. Because geologic site conditions vary, reporting requirements have focused on the development and implementation of site-specific monitoring plans. These plans employ a suite of technologies to monitor the distribution of CO_2 in the storage formation and to detect leaks. Such monitoring plans are applied through the lifetime of a project. In addition, requirements for data collection and history-matching are also often included.[b] Such requirements ensure that risk assessment and CO_2 simulation models developed during site characterization are periodically recalibrated with real results as the injection proceeds. Instead of requiring specific monitoring tools, CCS regulations tend to employ a performance-based approach, where the operator must identify how a given set of criteria will be monitored and satisfy containment requirements. Important criteria for monitoring and data reporting are presented in Table 2, along with examples of monitoring tools. Regardless of the tools used, the monitoring plan should comprise a strategy designed to ensure that key information (labeled criteria in Table 2) is collected, assessed, and reported. Suitable monitoring areas are established to encompass the entire project footprint, including both the expected area of the injected CO_2 (i.e., CO_2 plume) and any area where the formation's fluid is expected to have a significantly elevated pressure.[c] The precise project footprint would then be evaluated and revised based on operational monitoring and reporting.

Box 3

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories

The *2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories* (hereafter, 2006 Guidelines) is the latest in a series of guidance documents provided by the IPCC to support the UNFCCC's greenhouse gas inventory reporting requirements. It is a revision of the 1996 Guidelines, and along with good practice documents[a] it provides the current methodology parties shall use to "estimate and report on anthropogenic emissions by sources and removals by sinks of greenhouse gases not controlled by the Montreal Protocol."[1] In 2011, the UNFCCC's Subsidiary Body for Scientific and Technological Advice (SBSTA) is expected to adopt the 2006 Guidelines as the methodological standard for inventories starting in 2015.[2]

While the 1996 Guidelines do not address industrial CCS, the 2006 Guidelines provide guidance on emission estimates for capture, transport, injection, and geologic storage of CO_2.[3,4] Notably, the 2006 Guidelines provide detailed (Tier 3) procedures for estimating emission from storage, including guidance on site characterization, assessment of leakage risk, modeling, monitoring, validating, and reporting. The 2006 Guidelines also address CO_2 used for enhanced oil and gas recovery and elucidate negative emissions obtained by capturing and storing CO_2 from biomass combustion.

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a. The *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* and the *Good Practice Guidance for Land Use, Land-Use Change and Forestry*

Sources:

1. UNFCCC. "Updated UNFCCC reporting guidelines on annual inventories following incorporation of the provisions of decision 14/CP.11. Note by the secretariat." Document code: FCCC/SBSTA/2006/9. Geneva, Switzerland: United Nations Office at Geneva, (18 Aug 2006). Available at: http://unfccc.int/documentation/documents/advanced_search/items/3594.php?rec=j&priref=600003988#beg.
2. UNFCCC Secretariat. "Use of the 2006 IPCC guidelines for national greenhouse gas inventors and revision of the UNFCCC reporting guidelines for Annex I Parties to the Convention." Available at: http://unfccc.int/national_reports/annex_i_ghg_inventories/ reporting_requirements/items/5333.php.

Research is underway to develop new tools for MMV and to test existing tools in commercial-scale demonstrations. As governments propose and adopt CCS regulations, the emerging global

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a. The authors recognize that a CCS regulatory framework may need to be designed to fit within the context of already existing environmental laws.

b. Comparing actual monitoring results with what computer models predicted, and in turn improving the models.

c. The "formation fluid" includes the stored CO_2, often combined with brine or other fluids already extant in the geologic formation.

approach to MMV typically allows for flexibility in monitoring tools and establishes a project footprint and monitoring area that extends beyond the CO_2 itself. Monitoring duration is an issue where there seems to be a lack of consensus among national regulations. This uncertainty likely results because there is no universal, scientific prescription that can recommend monitoring for a given number of years; the best solutions are site-specific options. The alternative is to utilize a performance-based approach to monitoring duration and establish a set of criteria that must be demonstrated prior to cessation of monitoring and are aimed at demonstrating that the stored CO_2 is permanently contained and will not harm human health or the environment in the future.[d] The relevant criteria developed in the WRI CCS Guidelines process are described in detail in the liability section of this paper (see page 15).

As **UNFCCC negotiators** consider MMV for internationally supported projects or Annex I accounting for reported CCS projects, we recommend that:

- a site-specific monitoring plan is developed and implemented over the full project footprint;
- procedures are in place to ensure that monitoring data are collected, reported, and reviewed; and
- a set of criteria be established to determine whether and when it is safe for any specific project monitoring to cease (see Liability section for proposed criteria).

Furthermore, the UNFCCC should not approve or support CCS projects that cannot satisfy these criteria and should support capacity building for countries without experience in implementing MMV for CCS projects.

As **national governments** consider addressing MMV for CCS, we recommend that a national environmental health and safety regulatory framework be established at the national or provincial/state level and that it includes MMV requirements that necessitate an operator appropriately monitors and reports key information, including at a minimum the criteria listed in Table 2. MMV efforts should also cover the entire project footprint and be continued until the operator demonstrates, and the regulatory authority agrees, that it is safe to cease monitoring (based on established performance-based criteria for site closure, either alone or in combination with a standard period of time).

Table 2 **Criteria for CCS Monitoring and Example Monitoring Approaches**

Criteria	Example Monitoring Approaches
Injected Volume	Flow meter
Injection Pressure or Rate	Pressure meter
Composition of CO_2	Chemical analysis of injectate
Spatial Distribution of CO_2 Plume	Time-lapse seismic, satellite radar interferometry (InSAR), monitoring wells, microseismic, microgravity, vertical seismic profiling, crosswell seismic, formation fluid chemistry from monitoring zone
Reservoir Pressure and Temperature	Downhole pressure sensor, Bragg fiberoptic grating, thermocouples
Well Integrity	Cement casing and imaging logs, vertical seismic profiling, well-head detection devices, mechanical integrity testing
Amount of Any Measurable Leakage	Groundwater sampling, CO_2 monitoring, artificial tracers/isotopes, soil-gas surveys, LIDAR atmospheric eddy co-variance

Environmental impacts

A CCS project, like any industrial activity, poses some potential site-specific environmental impacts. In the UNFCCC context, two specific issues have been raised in submissions in the context of the discussions regarding inclusion of CCS in the CDM: the potential impurities in the CO_2 stream and the difficulty of incorporating CCS into an environmental impact statement or assessment (EIS or EIA).

Using available capture technologies to acquire CO_2 from various industrial facilities may result in CO_2 that contains trace impurities. For example, where oxygen-fired combustion is employed as a capture approach at a coal-fired power plant, the purity of the CO_2 can range from 80 to 98 percent.[2] Common co-constituents in the captured CO_2 from any industrial facility include trace amounts of sulfur dioxide (SO_2), nitrogen oxides (NO_X), hydrogen sulfide (H_2S), carbon monoxide (CO), methane (CH_4), nitrogen (N_2), argon (Ar), and oxygen (O_2).[25] The quantity of each co-constituent varies depending on the type of industrial facility and type of capture and compression units. Because H_2S poses human health and safety risks at low concentrations, its presence requires due diligence and extra precautions, although it should be noted that Canada has experience safely transporting and injecting H_2S-rich gases.[2]

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[d] Such an approach is described in the 2008 *Guidelines for Carbon Dioxide Capture, Transport, and Storage,* published by the World Resources Institute (WRI) (see page 103, part d).

Oxygen can also introduce technical challenges during storage by stimulating growth of microbiological organisms in the subsurface.[25]

In the context of the existing national environmental regulatory frameworks for CCS, regulators have provided many definitions of the CO_2 stream to be injected, ranging from "greenhouse gas" (Australia) to "[consisting] overwhelmingly of CO_2" (EU).[33] The EU requires that concentrations of any co-constituents be below levels that would affect the integrity of the transport infrastructure and storage site or pose a risk to human health or the environment.[33] In this context, a composition analysis of the CO_2 stream is required and serves as a key component in the site-specific risk analysis.

A number of comprehensive EIS efforts for CCS projects have been completed while incorporating the long-term leakage risks (see list in Appendix B). These EIS efforts have considered risk scenarios and analyzed potential impacts of a project over time while including public participation and a review of draft documentation. A comprehensive EIS will evaluate the full range of potential environmental impacts, including consumption of energy and cooling water, which may be increased when CCS is incorporated into an existing power plant or other industrial facility. Researchers have also raised concerns over potential eutrophication[e] from nitrogen compounds utilized in certain CO_2 capture technologies (such as amines) as well as possible contamination from heavy metals mobilized by CO_2 stored in the subsurface.[34,35,36]

CCS's environmental impacts are the subject of current research and not explored in detail here. As pilot and commercial-scale demonstrations proceed, research can help identify opportunities to lower CCS facilities' extra energy and water consumption and demonstrate and develop capture technologies that will minimize or eliminate the risk of eutrophication.[37,38] Additional research is also needed to refine methodologies for robust risk analysis and to further explore the possible leaching of heavy metals and other geochemical reactions that may occur in the subsurface.

To address the environmental impacts of CCS, we recommend that **UNFCCC negotiators**:

- establish criteria whereby the CO_2 purity of a potential project is incorporated into the site-specific risk analysis and management plan,
- ensure that supported projects have been subject to an EIS and risk assessment, and
- review and assess EIS and risk assessment documents in determining whether to support a CCS project.

As **national governments** consider how to address CCS's environmental impacts, we recommend that a robust environmental regulatory framework be established for CCS and that this framework requires:

- a compositional analysis of the CO_2 stream and
- the use of the details of the analysis as part of the site-specific risk assessment.

Moreover, all CCS efforts should be subject to a comprehensive EIS analysis that includes an analysis of the risk of leakage over time and public participation in the EIS process, either via public hearings or more involved public consultation engagement.

Project activity boundaries

Parties have raised concerns regarding project activity boundaries because of the challenges in capturing all relevant emissions, the potential for projects to span international boundaries, and the challenge associated with defining the spatial and temporal boundaries of a CCS project.[3] As described in the MMV section, there are some technical and temporal challenges when establishing a physical (or spatial) project boundary for a CO_2 storage effort. As illustrated in Figure 4, the size of the injected CO_2 plume increases over time, and the impacted area will extend beyond the CO_2 itself. The physical project boundary also includes any infrastructure associated with CO_2 capture and transportation.

Additional research is currently underway to identify how the CO_2 plumes and areas of elevated pressure from different wells interact in the subsurface. Moreover, any one project may include several points of injection that together with their associated injected CO_2 plumes comprise the spatial project boundary. However, the uncertainty in precisely locating the plume decreases over time as operational monitoring data is incorporated into the computational simulation and the models and risk analysis are updated. After injection stops, the rate of CO_2 migration within the storage reservoir decreases.

Project boundaries are also important from a GHG accounting perspective. In this respect, establishing a CCS project boundary is not substantially different from establishing a boundary for other mitigation projects. Where there is a significant energy penalty (such as CCS combined with power production),

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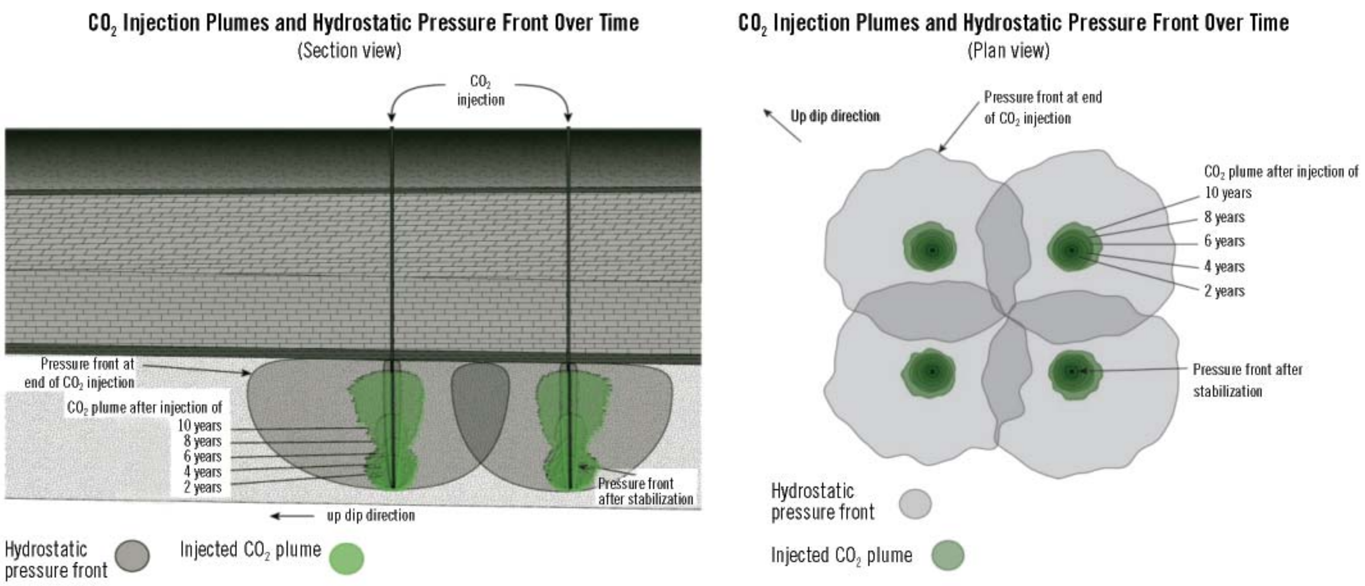
[e] Eutrophication is the significant growth of algae and other aquatic species in the presence of artificial nutrients.

FIGURE 4 Changes in CO_2 Project Footprint Over the Lifetime of a Project



Source: Image courtesy of the Illinois State Geologic Survey.

the emissions associated with the increased energy use should be taken into account when estimating the reduction associated with the stored CO_2. A decision will also need to be made for CCS on whether project boundaries should be extended to include the life cycle emissions, including the upstream GHGs associated with mining and transporting coal or other input to the industrial site. It is essential that any fugitive emissions from the project's capture and transport stages be accounted for, along with any detected CO_2 leakage from the subsurface. The emissions reductions from a CCS project are generally measured by the volume of CO_2 injected, minus the fugitive emissions and the impact of the energy penalty, as described in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, (see Box 3). As experience is gained in reporting and verifying emissions from CCS projects, the methodology for establishing spatial and temporal boundaries can be improved and should be updated at least once every decade. The EU Emissions Trading Scheme has another detailed methodology following the same principles.[39]

Methodologies for establishing the spatial boundary of a CCS project are already being incorporated into environmental regulatory frameworks for CCS, such as the EU Directive for Geologic Storage. These methodologies employ simulation and risk assessment as described in the MMV section and include the land area of the full project footprint (including that above the plume's predicted location) over the lifetime of the CCS project.[40]

As **UNFCCC negotiators** consider the technical and legal basis of establishing project boundaries for CCS, we recommend that prior to a decision (for example, by the CDM methodology panel) on whether to support a project, the UNFCCC should ensure that:

- an accurate project boundary has been established and
- best practice MMV methodologies for emissions reduction accounting will be employed for CCS in the relevant sectors.

As **national governments** consider project boundaries for CCS efforts, we recommend the establishment of an environmental health and safety regulatory framework that requires a monitoring area and project footprint be defined based on site-specific data, simulations of the CO_2 injection, and a comprehensive risk analysis. This effort must also be supported by established methodologies for calculating and reporting the GHG reductions from CCS projects.

International law

Some Parties have expressed concern over the lack of an international law governing CCS[f] because domestic regulations are not yet in place to inform the establishment of an international framework. Concern has also been raised because the relevant Marine Treaties were not designed to accommodate CCS. This section summarizes where international law has acknowledged CCS as a legitimate mechanism for CO_2 disposal and the international standards already in place for CCS.

International law becomes particularly important in cases where the physical project boundary crosses national borders, enters international waters, or enters national waters that are governed by international treaties.[g] Recent years have seen parties to a number of international marine treaties work to amend those treaties so that CCS projects are allowed under defined circumstances. For example, the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Convention) and the Protocol of 1996 (London Protocol) have been amended to allow and control CCS.[41,42,43,44,45] In the context of the London Convention, a framework for risk assessment and management was developed and adopted, and it includes guidelines for management as well as site selection, EIA, and monitoring.[45,46] In 2006, the London Protocol, which prohibits ocean disposal of any material not specified in the Protocol, was amended to allow "CO_2 streams from CO_2 capture processes" for sub-seabed CO_2 storage.[44,47] Article 6 of the Protocol was also recently amended to allow for the export of CO_2 for CCS purposes.[45] Moreover, the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) has also addressed CCS.[48] Although OSPAR does not have the global implications of the London Convention, it includes 15 countries and the EU.[49] Mirroring the changes to the London Convention, OSPAR was amended in 2007 to allow CCS, and guidelines for risk assessment and management were adopted.[48]

Although these actions allow CCS under international treaties, CCS projects that have spatial project boundaries that span national borders will require coordination and regulatory approval from both host governments. In its directive concerning CO_2 storage, the EU requires member state authorities to jointly meet the regulatory requirements.[33] Under the London Protocol, countries wishing to undertake transboundary CCS projects are required to enter into an agreement on their respective responsibilities. The *2006 IPCC Guidelines for National Greenhouse Gas Inventories* also include provisions for reporting emissions from transboundary CCS projects.

As **UNFCCC negotiators** consider international law governing CCS, we recommend that the London Protocol guidelines for risk assessment and management be applied by the UNFCCC.

As **national governments** consider international law for CCS, we recommend that they apply the rules and guidelines as outlined under the relevant existing treaties and agreements.

Liability

The lack of established procedures for addressing short- and long-term liability for CCS has been raised as a concern. The term liability in a CCS context includes:

- financial compensation for the affected individuals or entities in the event of unexpected leakage that harms people or the environment,
- carbon liabilities associated with international trading schemes and other national market mechanisms, and
- post-closure stewardship (routine maintenance and monitoring) of CCS sites.

As with many aspects of CCS, potential impacts and liabilities are often site specific. While some broad categories of possible impacts exist (e.g., release of CO_2 to the atmosphere, CO_2 leaking from storage complex and into underground sources of drinking water, etc.), the actual probabilities of these events occurring and their associated liabilities are currently determined on a site-specific basis. Efforts are being made to provide broad estimates for risks and liabilities as the research evolves.

At the time that CCS discussions first began in the UNFCCC, there were no policies that provided national, state, or provincial clarity on long-term stewardship and liability for CCS. A range of policy options and approaches are now being implemented, as summarized in Table 3. Most of these policies require that the liability and stewardship responsibilities for a CCS effort rest with the project operator until injection ceases and a post-closure monitoring period has been completed to the satisfaction of a regulatory authority. Some governments have elected to after the post-closure period assume the liability either for specific CCS projects that they sponsor or for CCS projects more broadly. Such transfer of responsibility is usually contingent

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[f] For example, see a recent submission to the 32nd session of the Subsidiary Body for Scientific and Technological Advice (SBSTA): *Views Related to Carbon Dioxide Capture and Storage in Geological Formations as a Possible Mitigation Technology*, available at: http://unfccc.int/resource/docs/2010/sbsta/eng/misc02a01.pdf.

[g] Carbon dioxide (CO_2) storage is not expected to occur, and is often forbidden, in the water column. The water column is defined here as the continuous vertical mass of water from the surface to the bottom sediments of a water body. However, a project boundary includes the land (and water) above the CO_2 plume's extent in a given geologic formation.

on issuance of a site-closure certificate, which is granted when the operator has met the agreed upon financial and monitoring obligations and the site has been determined by a regulatory authority to not pose a significant threat of endangering people or ecosystems. The costs of stewardship are often linked with liability and are funded by a fee paid by the project operator in advance, typically during the injection phase.

Many NGOs assert that the operator should remain responsible for liability and post-closure stewardship indefinitely, because such responsibility encourages due diligence in safe operations.[50] However, industry CCS experts argue that the uncertainty regarding such first-of-a-kind CCS efforts warrants government support, and in some cases indemnification.[51] Many other experts feel that industry should be responsible during the operational phases of a project and immediately after injection but concede that the government is the only entity that might exist long enough to provide the long-term oversight necessary for a storage site.

Additional research and discussion is needed in this area. Because the first CCS projects are just being initiated, there is little available information on the actual costs of post-closure stewardship and liability coverage. In addition, the approaches taken for the first CCS projects might be revised as additional experience with the technology is gained. For example, a liability framework for the first projects might have the government assume liability after operations cease, but in the future, mechanisms should be designed to internalize long-term costs for monitoring, stewardship, and liability in the planning and operation of a CCS project.

A key point in the discussions around liability is determining whether and when responsibility could be transferred to the government or another entity. As mentioned in the MMV section, WRI's CCS Guidelines[h] provide a set of criteria designed to ensure that a given CCS effort is not expected to pose a risk to human health or the environment in the future. Specifically, these criteria include a demonstration of all of the following:

1. The estimated magnitude and extent of the project footprint, based on measurements and modeling
2. That CO_2 movement and pressure changes match model predictions
3. The estimated location of the detectable CO_2 plume based on measurement and modeling
4. Either (a) no evidence of significant leakage of injected or displaced fluids into formations outside the confining zone or (b) the integrity of the confining zone
5. That, based on the most recent geologic understanding of the site, including monitoring data and modeling, the injected or displaced fluids are not expected to migrate in the future in a manner that encounters a potential leakage pathway
6. That wells at the site are not leaking and have maintained integrity

As **UNFCCC negotiators** consider liability for CCS projects, we recommend procedures be established for ensuring that post-closure stewardship and liability will be managed by a

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[h] The World Resources Institute's *Guidelines for Carbon Dioxide, Capture, Transport, and Storage*

Table 3 Approaches to CCS Liability in Place in Key Countries and Regions

Jurisdiction	CCS Liability Framework	Application
Australia	The Australian Government accepted 80 percent and the Western Australian Government accepted 20 percent of any post-closure liability for CCS in the long term.	Gorgon liquified natural gas project
Canada	There is no unique liability for CCS; it is governed by the same rules as oil and gas operations, although provincial rules are under consideration in Alberta and Saskatchewan.	All CCS projects
European Union	Liability and responsibility for CCS is transferred to the member state's "competent authority" after operator proves that there is no risk of leakage and completes 20 years of post-closure monitoring.	All CCS projects
United States	State-level policies are in place in seven states (Illinois, Kansas, Louisiana, Montana, North Dakota, Texas, and Wyoming) and include a variety of policy approaches from operator retains liability to state accepts full liability/responsibility. No national framework for CCS liability exists.	All CCS projects in select states
United Kingdom	Adopted the EU directive, with the government acting as the "competent authority".	All CCS projects

competent institution—such as the operator, the government, or another authority—over the long-term. The procedures should be clarified and in place in advance of project support. These mechanisms should be designed to internalize long-term costs for monitoring, stewardship, and liability in the planning and operation of a CCS project.

As **national governments** consider liability for CCS efforts, we recommend that procedures for transfer of responsibility be clearly articulated and based on the list of criteria provided in this section and expanded upon in WRI's CCS Guidelines. Where responsibility will not be transferred to the host government, the responsibilities of the project operator over the long-term should be clearly articulated to include both post-closure stewardship and liability.

Safety

Human health and safety has been the topic of considerable research on CCS and is the primary focus of risk assessment, management, monitoring, and mitigation approaches. However, concerns remain because CO_2 is an asphyxiant at high concentrations.[52,53,54] The risks of exposure to such high concentrations of CO_2 are greatest during the operational phases of a project and are borne primarily by on-site workers. However, safety over the long-term storage time frame must also be considered, even if long-term leaks are not expected.

Industry experience with underground injection of CO_2 for EOR indicates that the operational risks of worker exposure to CO_2 can be managed with existing industry best practices for workplace safety and by controlling injections to avoid well blowouts or other incidents that could expose people to high concentrations of CO_2.[25]

While CO_2 disperses readily in turbulent air, a concern is that slow leaks could result in long-term exposure to low CO_2 concentrations and might go undetected. Similarly, CO_2 could pool in a low-lying area such as a valley, basement, or a body of water, and it could pose a threat if not detected and mitigated. While these slow leaks could arise from capture, transport, or storage steps, it is typically investigated as a risk associated with storage. While still a subject of continued research, this concern is being addressed by establishing guidelines, regulations, and due diligence in risk analysis, project siting, and monitoring that extends over the lifetime of a project, as has been described in other areas of this paper. CCS projects should be addressed on a site-specific basis and should not move forward where there are risks of human or ecosystem exposure that cannot be managed.

As **UNFCCC negotiators** consider the safety of a CCS project, they should adopt the recommendations outlined in this paper for non-permanence, risk assessment, EISs, and MMV, as discussed previously.

As **national governments** consider the safety of CCS, they should ensure that worker safety laws apply to CCS projects and that mechanisms are in place for an environmental regulatory framework that protects people and the environment from potential exposure to the captured and stored CO_2 during all phases of a CCS project. For example, standards for capture facilities or pipeline and well construction would be key safety components of such a framework. CCS projects should not be conducted where they cannot be done safely.

Insurance coverage and compensation for damages due to seepage or leakage

Over the past year, Parties and NGOs have debated whether project insurance should be compulsory for CCS efforts.[55,56] Insurance policies are available for operating CCS projects, and such policies are typically renewed on an annual basis. These policies are being designed based on the current understanding of risk management in CCS projects and will likely evolve over time. Insurance coverage is already available to serve as the primary mechanism for compensation of damages during the operational phases of a CCS project. In addition, large companies can "self-insure." Some experts have questioned whether insurance is the most effective or appropriate mechanism for CCS, as other financial security mechanisms are available and could be employed to the same end.[57]

Over the long term, where the responsibility for liability and stewardship might transfer to the government, a trust fund or other mechanism for funding any unexpected damages is often considered.[58] For example, a trust fund might be established with funding collected from the CCS project operators on a fee-per-ton-of-CO_2 basis. As the first commercial CCS demonstration projects are conducted, the results of the site-specific risk analysis can be used to estimate the costs of possible damages and influence trust fund design for compensation of longer-term damages. Intelligent trust fund design will be needed to ensure that trusts remain effective and robust. For example, in a 2009 article, Dooley et al.[59] propose that a fund should be established with (1) strong oversight regarding CCS site selection and fund management and (2) a clear process for periodically valuing the funds and mapping the fund to the risk profile of the pool of covered CCS projects.

UNFCCC negotiators should require that CCS projects recognized under the UNFCCC have insurance (or equivalent coverage with other financial security mechanisms, if, for example, self-insured) as well as a mechanism for compensating any damages incurred in the long term and providing funding for any corrective actions (either by insurance or a host-government trust fund).

As **national governments** consider the design of trust fund mechanisms that might complement insurance policies available during the operational phases of a project, they should ensure that the appropriate oversight and periodic valuation are in place. National environmental regulations for CCS projects should ensure that insurance is required up until a point where responsibility might transfer to the government or another competent entity, and that the entity receiving responsibility can itself provide for insurance.

RECOMMENDATIONS AND CONCLUSIONS

Many of the issues concerning CCS that have been raised in the UNFCCC context can be addressed given the current state of knowledge. As additional research is completed and the technology is demonstrated at commercial scale, CCS's technical aspects and policy implications will become clearer and better understood. This paper reviewed the nine issues raised in the latest round of discussions and provided recommendations for next steps by the UNFCCC and national governments that can facilitate addressing these issues. These recommendations can be implemented through criteria, best practices, procedures, or other functions attributed to any number of proposed UNFCCC structures that could guide future deployment of commercial-scale CCS projects and further research into specific areas. Our recommendations are summarized in Table 1 at the beginning of this document.

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Appendix A: CCS Issues Raised in the UNFCCC, COP10 through COP15

Conference of the Parties (COP) 10, Montreal, 2005:

- Project boundary
- Leakage
- Permanence

COP12, Nairobi, 2006:

- Long-term physical leakage (seepage) levels of risks and uncertainty
- Project boundary issues (such as reservoirs in international waters, several projects using one reservoir) and projects involving more than one country (projects that cross national boundaries)
- Long-term responsibility for monitoring the reservoir and any remediation measures that may be necessary after the end of the crediting period
- Long-term liability for storage sites
- Accounting options for any long-term seepage from reservoirs
- Criteria and steps for the selection of suitable storage sites with respect to the potential for release of greenhouse gases
- Potential leakage paths and site characteristics and monitoring methodologies for physical leakage (seepage) from the storage site and related infrastructure for example, transportation
- Operation of reservoirs (for example, well-sealing and abandonment procedures), dynamics of carbon dioxide (CO_2) distribution within the reservoir and remediation issues
- Any other relevant matters, including environmental impacts

COP13, Bali, 2007 (issues identified in informal discussions)[60]

- Implications of CCS activities for other Clean Development Mechanism (CDM) activities
- Long-term monitoring of leakage (seepage) and coverage area of monitoring
- Liability issues relating to the difference in time periods between the crediting period and closure of the reservoir
- Possible implications of the additional revenue generated by the CDM on increased fossil fuel production
- Relevant regulatory approaches to CCS
- Project boundary issues and projects involving more than one country
- A possible process to deal with technical issues

COP14, Poznan, 2008

- No issues identified

COP15, Copenhagen, 2009

- Non-permanence, including long-term permanence
- Measuring, reporting and verification (MRV)
- Environmental impacts
- Project activity boundaries
- International law
- Liability
- The potential for perverse outcomes
- Safety
- Insurance coverage and compensation for damages caused due to seepage or leakage

APPENDIX B: KEY TECHNICAL RESOURCES BY ISSUE

Long-Term Permanence

Intergovernmental Panel on Climate Change (IPCC)'s *Special Report on Carbon Dioxide Capture and Storage*
http://www.ipcc.ch/publications_and_data/publications_and_data_reports_carbon_dioxide.htm

International Energy Agency Greenhouse Gas R&D Programme (IEAGHG)'s *Geological Storage of Carbon Dioxide: Staying Safely Underground*
http://www.co2crc.com.au/dls/external/geostoragesafe-IEA.pdf (see page 16)

IEAGHG Risk Scenarios Database
http://www.ieaghg.org/index.php?/20091223132/risk-scenarios-database.html

World Resources Institute's *Guidelines for Carbon Dioxide Capture, Transport, and Storage*
http://www.wri.org/publication/ccs-guidelines

Measurement, Monitoring, and Verification

2006 IPCC Guidelines for National Greenhouse Gas Inventories Vol. 2: Energy. Chapter 5: Carbon Dioxide Transport, Injection and Geological Storage
http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html

Eggleston, H.S. "Estimation of Emissions from CO_2 Capture and Storage: the 2006 IPCC Guidelines for National Greenhouse Gas Inventories." UNFCCC Meeting: SB 24 & AWG: In-session workshop on carbon dioxide capture and storage, May 20 2006.
http://unfccc.int/files/meetings/workshops/other_meetings/2006/application/pdf/ccs_20060723.pdf

Environmental Impacts

World Resources Institute's *Guidelines for Carbon Dioxide Capture, Transport, and Storage*
http://www.wri.org/publication/ccs-guidelines

Example environmental impact statements (EISs):

- Gorgon Project, Australia:
  http://www.epa.wa.gov.au/docs/gorgon/EIS_Gorgon_ERMP.pdf
- FutureGen Project, United States:
  http://www.netl.doe.gov/technologies/coalpower/futuregen/eis/

Project Activity Boundaries

Greenhouse Gas Protocol's Project Protocol
http://www.ghgprotocol.org/standards/project-protocol

International Law

International Maritime Organization's *Risk Assessment and Management Framework for CO_2 Sequestration in Sub-Seabed Geological Structures*
http://www.imo.org/Environment/mainframe.asp?topic_id=1615

Liability

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Insurance

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