Submission of views from the United Arab Emirates on addressing the issues referred to in paragraph 3 of FCCC/CMP/2010/L.10 in the modalities and procedures for the inclusion of carbon dioxide capture and storage (CCS) in geological formations as clean development mechanism project activities

Contents

Executive Summary

CO_2 capture and storage in deep geological formations (e.g., depleted oil and gas reservoirs, aquifers, salt domes, etc.) has emerged as one of the most viable and promising technologies for effective large scale reduction of CO_2 emissions. World-wide experience with CCUS projects has been gaining momentum and proves that CO_2 can be stored safely and permanently without significant leakage. There are around 80 large scale integrated projects at various stages of the asset lifecycle, and a total of almost 200 active projects at various scales and stages of the CCS chain globally. The vast majority of these are in developed countries.[1]

The eligibility of Carbon Capture and permanent Storage (CCS) projects as CDM projects is critical in meeting GHG emissions reductions targets to mitigate climate change, providing energy security and economic stability, and ensuring that this important technology is successfully transferred to developing countries.

A summary of the responses to the issues raised by the CMP regarding the acceptance of CCS in the CDM follows:

- **The importance of site selection and characterization**
  The importance of site selection and site characterization in order to ensure safe CO_2 storage and long-term permanence of containment is widely recognized. These issues are addressed by a variety of guidance documents, including the recently issued EU Directives and DNV's CO2QUALSTORE best practice guidelines. We would suggest the EB use these guidelines to inform the development of their own site selection criteria. Furthermore, the undertaking of such challenges is well within the capabilities of National Oil Companies, such as the Abu Dhabi National Oil Company (ADNOC). Geological CO_2 storage can be safely and securely accomplished in a variety of geological settings such as depleted gas fields, depleted or active oil fields, deep saline aquifers, deep coal seams, caverns, salt domes and organic rich shales. As a requirement, the selected geological sites should have good CO_2 injectivity, adequate storage capacity, good sealing cap rock, and stable geological settings/environment.

- **The scope and role of risk assessments in CCS projects**
  A wide-scope, dynamic, continuously refined and updated dynamic risk management and mitigation (DRMM) strategy should be developed and integrated throughout the CCS project lifecycle as a requirement. DRMM should commence at a very high level during the first stages of site screening, and should include safety, social, environmental and economic factors. DRMM should be further refined as the site selection process progresses, ultimately resulting in site-specific performance-assessment-based frameworks that quantify adverse consequences and event likelihood while keeping track of key uncertainties. Besides shaping the ultimate storage site selection, the final DRMM assessment should form the

[1] Global CCS Institute. "The Status of CCS Projects: Interim Report." 2010.

basis of the monitoring and measurement program, as well as shape the corrective measures strategy.

- **Strict monitoring requirements**
  A comprehensive quantitative understanding of the reservoir is required prior to, during, and after the injection of CO_2. By combining model predictions and concrete measurements one can be in a position to generate predictions (CO_2 migration path and CO_2 process performance) that are physically realistic and also consistent with field data. CCUS projects require multiple types of observations, each sensitive to different physical and chemical properties acting over different spatial and temporal scales. The procedure linking monitoring data and models will be an ensemble data assimilation algorithm that will use the models to generate a set of possible system descriptions, all consistent with monitoring observations. This makes it possible to provide a cost-benefit analysis of the importance of different data types, as well as to design robust operating and monitoring strategies that can work well over a range of conditions.

- **The applicability of modeling for CCS projects**
  Development of a reliable modeling framework (analytical models and an accurate and robust coupled compositional fluid flow and geomechanics simulator) is the most critical scientific and engineering challenge that must be tackled and resolved in order to be able to make realistic and accurate subsurface performance forecast of CO_2 utilization and permanent sequestration processes. Modeling is an essential part of any risk based project and is routinely used in oil and gas field management and decision making. Modeling *complements,* and does not replace monitoring.

- **Project boundaries**
  CCS project boundaries should include all surface facilities as well as an extended portion of the subsurface. It is important to note that an element of flexibility should be maintained with respect to the lateral boundaries of the subsurface in case CO_2 migrates across such lateral boundaries but remains safely contained.

- **Accounting for seepage**
  Geochemical and surface monitoring must be performed in order to detect, measure, and account for any CO_2 seepage from the storage.

- **Liability**
  Overall liability should be with the project proponent especially throughout the project life cycle, followed by long term liability under host country responsibility.

1. Introduction

The United Arab Emirates welcomes the decision of the Conference of the Parties to include CCS under the clean development mechanism as stated in the CMP.16 on carbon dioxide capture and storage in geological formations as clean development mechanism project activities, providing that issues raised and identified in decision 2/CMP.5 paragraph 29 are addressed and resolved in a satisfactory manner. The United Arab Emirates also welcomes the invitation to address these issues. Accordingly, we hereby submit our views and recommendations on how to address them in the modalities and procedures.

As noted by the IEA (World Energy Outlook 2010[2], and Energy Poverty Report[3]), the need to keep pace with rising global energy demand means that fossil fuel will continue to play a central role in the global energy mix for the foreseeable future. CCS is therefore an indispensible component of a broader strategy to tackle the challenge of climate change and limit the global average temperature rise to 2 degrees Celsius above pre-industrial levels. The use of CCS can and should complement other approaches to to ensuring a balanced energy portfolio, such as increased efficiency and the promotion of renewable energy. This balance is essential to addressing climate change while still providing reliable, affordable energy for the developing world.

Yet CCS projects still face considerable barriers, particularly barriers related to cost. The inclusion of CCS under the CDM will help to address these cost-related and other barriers, paving the way for the transfer of this important technology to developing countries.

Many governments have perceived an immediate need to start taking measures to reduce CO_2 emission into the atmosphere. One such measure is carbon capture from power generation stations and storage in geological structures such as oil and gas reservoirs or aquifers.

The United Arab Emirates (UAE), as a result of its rapid population and economic growth, has one of the highest carbon footprints per capita in the world. The Abu Dhabi government has established an ambitious plan to capture CO_2 from a wide range of large carbon emitting industrial plants, and transport it through pipelines to inject it for enhanced oil recovery and/or subsurface storage in geological formations. This is one way in which the UAE and, especially, Abu Dhabi, is taking steps towards reducing greenhouse gas emissions and, ultimately, achieving carbon neutrality. Indeed, carbon capture use and storage (CCUS) has emerged as a critical enabling technology for the continued use of fossil fuels in a carbon constrained world with minimizing the carbon footprint of this energy source.

[2] International Energy Agency. “World Energy Outlook.” 2010.
[3] International Energy Agency. “Energy Poverty Report.” 2010.

1.1. Purpose /scope of submission

This submission considers the issues raised in **Decision -/CMP.6 on "Carbon dioxide capture and storage in geological formations as clean development mechanism project activities"** at *The Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol, Recalling* decisions 7/CMP.1, 1/CMP.2, 2/CMP.4 and 2/CMP.5, *Taking into account* Article 12, paragraph 5(b) and 5(c), of the Kyoto Protocol.

Our comments focus mainly on the subsurface storage issues related to carbon capture and storage. We believe that issues related to the capture and transportation components of the CCS chain can be addressed under the already existing modalities and procedures under the CDM.

2. Issues listed in the Draft decision -/CMP.16 to be addressed by the CDM modalities and procedures

2.1. Site Selection

2.1.1 Description of technical issue to be addressed

Site selection of CCS projects is determined by the suitability of a geological formation for use as a storage reservoir. Suitability is determined by a site's geology, tectonic regime, depth of burial, surface characteristics, likely trapping mechanisms, and anticipated seepage pathways.

A geological formation should only be selected as a storage reservoir if, under the proposed conditions of use, no significant risk of either seepage or contamination exists. We recommend the development of a standard definition of what constitutes "significant risk."

> **Draft Decision Paragraph 3**
>
> **Subparagraph (a):** The selection of the storage site for carbon dioxide capture and storage in geological formations shall be based on stringent and robust criteria in order to seek to ensure the long term permanence of the storage of carbon dioxide and the long-term integrity of the storage site;
>
> **Subparagraph (d)** The criteria for site selection and monitoring plans shall be decided upon by the Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol and may draw upon relevant guidelines by international bodies, such as the 2006 IPCC Guidelines for National Greenhouse Gas Inventories;

2.1.2 Recommendations on addressing site selection in modalities and procedures

Because each site is unique, a project proponent applying for a CCS project under the CDM should be required to include a comprehensive and clear explanation of the suitability of their proposed site. Following the suggestion made by the IPCC in their Special Report on Carbon Dioxide Capture and Storage, at minimum, sites must (1) have adequate capacity and injectivity, (2) include a satisfactory sealing caprock or confining unit and (3) consist of a sufficiently stable geological environment to avoid compromising the integrity of the storage site.

CDM project participants engaging in CCS activities should also be required follow state-of-the-art site selection procedures which follow guidance set out by national or international standards or legislation. The Executive Board (EB) should refer to the selection criteria set out in the EU Directive on the geological storage of carbon dioxide[4] or as described in the guidelines

[4] Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide.

prepared by DNV in CO2QUALSTORE [9] as examples of “best practice” as they undertake the development of their own guidelines on site selection.

For each site, a site selection assessment should be undertaken, and should include a risk assessment as well as a risk mitigation plan. Minimum site criteria should be met, and uncertainty with respect to seepage should be addressed in more stringent monitoring requirements. The EB should develop a standardized definition of minimum site criteria, and establish an uncertainty threshold below which the application of more stringent monitoring requirements are applied. Overall, the UAE believes that significant seepage is unlikely if CCS projects are selected carefully, operated in strict adherence to regulations, and responsibly monitored over long time frames.

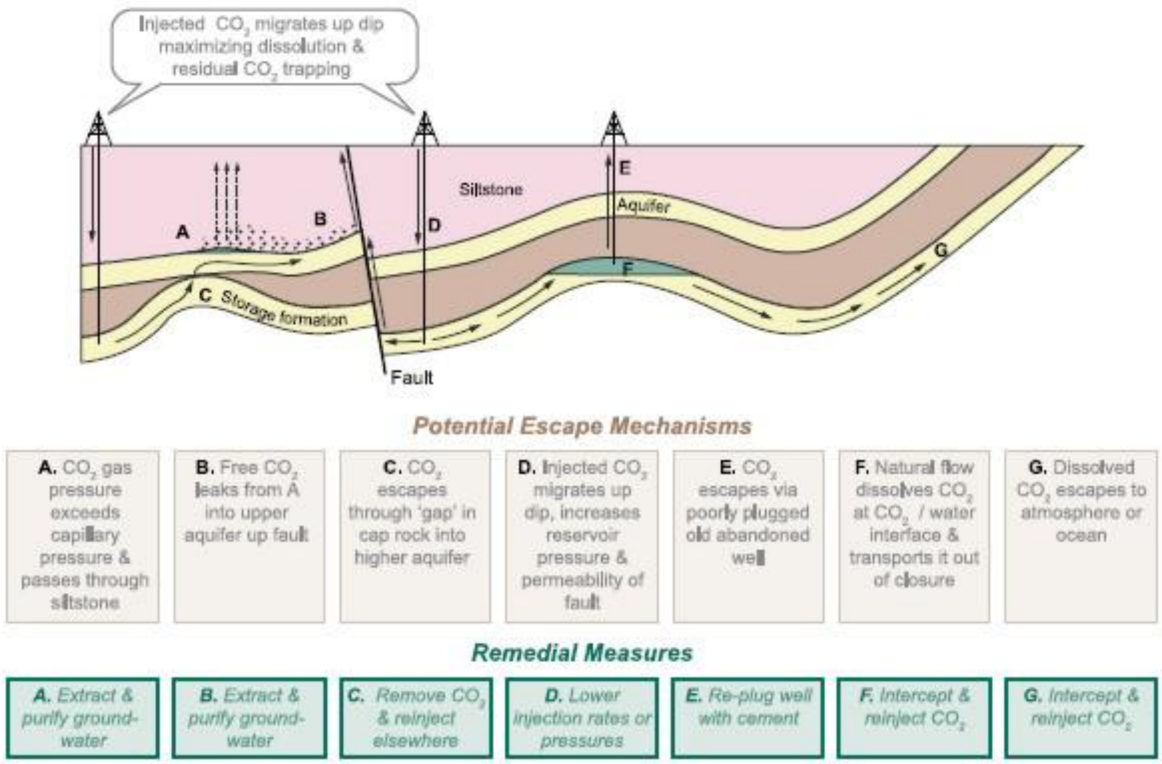

Fig. 1: Potential escape routes for CO_2 injected into saline formations, and remedial measures (from IPCC, 2005)[5]

In addition, any site assessment should have to be approved by a national authority relevant to the sector, before it is submitted to the UNFCCC and considered as CDM project.

The UAE recommends that site selection be addressed in the CDM modalities and procedures by using the methodology proposed below.

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[5] IPCC Special Report on Carbon Dioxide Capture and Storage. 2005.

Proposed Site Selection Methodology

Information Input Requirements

i. Geologic information including descriptions of the geologic units above and within the reservoir, locations of mapped faults, and information about the regional tectonics including the regional stress field.

ii. Geophysical information including 3D seismic surveys, interpretations of processed results from the 3D surveys, and information about regional and local seismicity. Both raw and processed active seismic data will be needed to assess the continuity and thickness of the cap rock, existence of faults within the reservoir and caprock, and reservoir heterogeneity. Velocity models to be used for migration and any updated information about the velocity model, particularly for the reservoir and caprock regions will be essential for conducting future seismic and geomechanical modeling. Sonic logs taken above and within the reservoir will be useful for calibrating seismic data and as complementary information for use in interpretation of other geological and geophysical data.

iii. Geomechanical information that can be used to infer the state of stress within the reservoir and caprock. This information may be obtained from borehole data such as breakouts inferred from caliper and televiewer logs, minifrac results, or information about fracture anisotropy within the reservoir, and mud loss events. Any data from boreholes needs to have associated wellbore location information.

iv. Rock/fluid properties information will be needed about properties of both reservoir and caprocks, as well as fluid properties. Rock properties include permeability, porosity, and mineralogy, which are essential to determine the injectivity of the formation and the containment properties of the caprock. Fluid properties include salinity of the brine, which is key to assessing dissolution trapping. Both geological descriptions and results of geophysical measurements will be essential for evaluating the candidate sites.

v. Locations and information about all existing wells will be needed to assist in the interpretation of the geophysical and geological data. Wellbore trajectories will be helpful for placing well information within a 3D model of the reservoir region. In addition, this information will help to determine which wellbores can be used in monitoring of injections into the reservoir. Information about well completions will help to better characterize the likelihood of existing wells as potential seepage pathways for injected CO_2.

Individual Site Characterization Tasks[6]

i. **Compiling all available data** for each proposed site, evaluating data quality, and making recommendations for new data that needs to be collected. The goal is to ensure that all background information is available for studies that need to be conducted to both characterize the reservoir and determine possible mechanisms for escape of CO_2.
ii. **Conduct evaluation of available data** to make a preliminary assessment of storage capacity as well as discussing the challenges related to monitoring each site.
iii. **Delineation of the reservoir architecture** including known and inferred structures within the reservoir and caprock that will act as barriers or facilitators for migration of injected fluids. This will likely involve further analysis of active seismic data and evaluation of changes in the reservoir that have accompanied previous production from the reservoir.
iv. **Evaluation and ranking of potential target formations.** This will build upon the initial ranking performed by the project participant/project operator. The most important criterion is seepage risk, which depends upon the integrity of the seal, and injectivity. Capacity is also important, especially to ensure the ability to ramp up CCS operation over the next few decades.

In addition, in line with the recommendations set out in the external assessment report for the UNFCCC[7] and in the annotations of EB 50, we recommend that a CCS Working Group under the UNFCCC should be established to further elaborate and fully describe:

- Minimum criteria for CO_2 storage site characterization;
- Procedures for site selection, risk assessment, and mitigation plans, drawing on the existing knowledge base such as the EU directive, and DNV guidelines for site selection[8];
- A Code of Conduct for the operation and monitoring of reservoirs;
- In the case of CCUS projects, a requirement for a percentage of "breakthrough" to be recovered and re-injected in the reservoir in addition the CO_2 injected in the base case.

We would also suggest that suitable site selection for long-term permanence would benefit from the development of an international (or host country) environmental regulatory framework that provides guidance on storage security and includes clear criteria for site selection, risk assessment, monitoring, and long-term ownership.

[6] Abu Dhabi National Oil Company recommended guidelines.
[7] Implications of the Inclusion of Geological Carbon Dioxide Capture and Storage as CDM Project Activities, http://cdm.unfccc.int/EB/050/eb50annagan1.pdf
[8] CO2QUALSTORE – Guideline for Selection and Qualification of Sites and Projects for Geological Storage of CO_2, DNV, 2010; http://www.dnv.com/binaries/CO2QUALSTORE_guideline_tcm4-412142.pdf

2.2. Monitoring

2.2.1 Description of technical issue to be addressed

A project participant/project operator must sufficiently monitor their storage site to:

(i) detect seepage or contamination, and

(ii) estimate the flux of CO_2 released to the atmosphere or hydrosphere if such a release is detected.

Draft Decision Paragraph 3

Subparagraph (b) Stringent monitoring plans shall be in place and be applied during and beyond the crediting period in order to reduce the risk to the environmental integrity of carbon dioxide capture and storage in geological formations;

To enable this level of monitoring, the following types of measurements and assessments are important:

- Fluid pressures, displaced fluid characteristics, fluxes, and composition in injection for a sample of monitoring wells;
- Active seismic measurements ranging from cross-well, to VSP, to 4-D surface seismics;
- Passive seismic measurements, including measurements that rely on induced seismicity;
- Geodetic measurements, including data from existing or newly deployed GPS stations and InSAR surveys;
- Time-lapse microgravity and/or gradiometry measurements;
- Electrical resistance tomography;
- Geochemical and surface monitoring of atmospheric CO_2 concentrations;
- Detection of corrosion or degradation of the injection facilities;
- Comparison between the reported and forecast behavior of CO_2 in the storage complex; and
- Assessment of the effectiveness of any corrective measures taken.

A broad range of technologies and methods for monitoring CCS projects are available, and the decision of which to apply varies depending on the specific project site. We recommend as a reference guide Srivastava's comprehensive overview of various methods of monitoring CO_2 storage in deep geological formations (2009). His methods are subdivided into (i) atmospheric monitoring techniques, (ii) near surface monitoring techniques and (iii) subsurface monitoring techniques, and are explained in detail in the appendices I-III of Srivastava (2009) and Annex ii of EU directive[9].

[9] Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide.

2.2.2. Recommendations on addressing monitoring in modalities and procedures

Unlike existing CDM project activities, and their modalities and procedures, monitoring for carbon capture and storage activities should require three phases, namely (i) pre-project monitoring, (ii) monitoring during operation and injection and (iii) post injection operation. Monitoring will need to extend beyond the crediting period of the project; the appropriate length of that time period should be determined by the EB or CCS Working Group.

Monitoring plans will need to vary across each of these phases as well. There should be a requirement that the monitoring plan be updated frequently (at a minimum, every five years) to account for changes to the assessed risks, learning, technical developments, and the evolution of best practices; however, excessive administrative burden or cost should be avoided in the application of this requirement. Updated plans should be re-submitted to the Host country and EB for approval.

Reporting

In addition to existing requirements for CDM project monitoring, reporting and verification, it is recommended that for CCS CDM projects, the project participant/project operator be required to submit annually to the Host country and CDM-EB:

- Reports on the measurements and assessments listed above in section 2.2.1;
- The quantities and composition of the CO_2 streams captured in the reporting period;
- Proof of the maintenance of the sufficient funds to address both short and long term liabilities; and
- Other information the Host Country and CDM-EB reasonably considers relevant for the purposes of assessing compliance with relevant storage permit conditions.

Inspections

The Host Country and CDM-EB, or an independent verifier elected on their behalf, should have the authority to conduct routine and non-routine inspections of all storage reservoirs for the purposes of checking and promoting compliance. Inspections could include activities such as visits to the injection facilities, assessing the relevant injection and monitoring operations carried out by the project participant/project operator, and checking all relevant records kept by the project participant/project operator. Routine inspections should be required at least every 5 years, following at least one calendar month's prior written notice to the project participant/project operator. Non-routine inspections should also be carried out at the discretion of CDM-EB/host country, within the guidelines of reasonable frequency. Following each inspection, the inspector should be required to prepare a report on the results of the inspection. The report should evaluate compliance with the requirements of the storage permit and the project parameters as established in the Project Design Document (PDD), and indicate whether or not further action is necessary. The report must also be communicated to the project proponent/project operator concerned.

In line with the recommendations as set out in the external assessment report for the UNFCCC[10] and in the annotations of EB 50, page 15, we recommend further elaboration of, and commitment to, the following elements:

1) Monitoring methodologies should set overall objectives while leaving flexibility in the monitoring programme details, so as to allow the most appropriate monitoring techniques to be selected given specific geological situations.
2) For each project, the monitoring programme and techniques should be derived from the site characterisation and modelling for the particular site, and fully described in the PDD so that they can be assessed.
3) The EB might wish to consider developing criteria for the assessment of monitoring methodologies and plans for geological CO_2 storage.
4) Verification of monitored reductions in anthropogenic emissions of CCS CDM project activities requires a DOE with appropriate CCS expertise.
5) Impose a requirement that a country wishing to host a CCS CDM project activity must notify the UNFCCC that, conditional on the registration of a project, it will commit to the post-crediting period responsibility for monitoring.

(Source: implication of the Inclusion of Geological Carbon Dioxide Capture and Storage as CDM Project Activity (EB 50, Annotations, Annex 1, page 15)

Unlike the monitoring requirements under existing CDM modalities and procedures, which are limited to the credit period, we recommend including the provision of monitoring prior to and beyond the credit period. Furthermore, flexibility has to be given to the project participants to change and update the monitoring plan and obtain necessary approvals. The Executive Board should develop procedures to address changes to the monitoring plans, including an approval process via a DOE and a technical committee.

[10] Implications of the Inclusion of Geological Carbon Dioxide Capture and Storage as CDM Project Activities, http://cdm.unfccc.int/EB/050/eb50annagan1.pdf.

2.3. Modeling

2.3.1 Recommendations on addressing modeling in modalities and procedures

Draft Decision Paragraph 3

Subparagraph (c) Further consideration is required as regards the suitability of the use of modeling, taking into account the scientific uncertainties surrounding existing models, in meeting the stringency requirements of such monitoring plans, in particular taking into account the 2006 IPCC Guidelines for National Greenhouse Gas Inventories:

Modeling is not, and should not be used as a tool to calculate emission reduction volumes. It does however have a crucial and complementary role to play in evaluating and assessing the behavior of CO_2 injection, storage, CO_2 plume movement and trapping in the given geological formation. Data derived from monitoring is invaluable to update numerical models and to improve existing or future storage operations and vice versa.

Modeling is not a substitution for monitoring but should be seen as a tool to predict the storage behavior of CO_2 for a short, medium and long term period. Modeling should be used as a "living" tool, and all monitoring data should flow back into newer modeling to (i) ensure the suitability of the modeling previously done, and (ii) re-adjust the modeling in case of large variations. Adjustment is necessary so that the model can reflect not just the predictions, but the real CO_2 behavior in the geological formation at that time.

In turn, modeling can be utilized in two important integration processes: (i) using models to merge and interpret data (a process often called "data assimilation"), and (ii) using models and data together to design cost-effective real-time monitoring strategies.

The key to the successful implementation of a modeling approach is the use of an integrated multi-disciplinary team which can leverage experience gained in the oil and gas industry in dealing with subsurface uncertainty. Such a team must in turn develop a transparent model which allows reviewers to appreciate and challenge the assumptions/inputs.

Examples for the use of monitoring in combination with models can be demonstrated by the activities undertaken by Abu Dhabi National Oil Company (ADNOC) in developing their CCUS project. ADNOC has further performed various laboratory studies, simulation and surface facilities studies to develop a suitable model and mitigate risks for their CCUS project. See Annex 1 for more details.

The result of these models can be the generation of a risk matrix that can be used as a dynamic tool for decision-making and review by the EB. An example of such a matrix resulting from modeling is demonstrated below.

Categories	Sub-Categories	Elements	Rumailta Zone B		Al Dabb'iya Zone B		Al Dabb'iya TZ B		Bab Far North	
			Complexity	Uncertainty	Complexity	Uncertainty	Complexity	Uncertainty	Complexity	Uncertainty
Subsurface	Reservoir Properties	Horizontal Permeability Heterogeneity	4	4	4	4	3	3	4	4
		Vertical Permeability Heterogeneity	4	5	4	4	4	4	3	4
		Stylolite Presence and Development	4	2	3	3	3	3	2	2
		Reservoir Pay Thickness	4	4	4	4	4	4	4	4
		Reservoir Quality (RRT)	4	3	3	4	3	4	2	2
	Reservoir Structure & Gelogy	Structural Compartmentalization	4	4	4	3	3	3	5	5
		Faulting and Natural Fractures	5	4	4	3	3	3	4	4
		Reservoir Dip	5	5	5	4	4	4	4	4
	Reservoir Rock and Fluid Properties	Oil Properties	3	3	3	4	2	4	5	5
		EOR Injected Gas/Oil PVT	4	3	4	3	4	3	5	4
		EOR Injected Gas/Oil EOS	4	2	3	3	3	3	5	4
		EOR Injected Gas/Oil MMP	5	4	4	4	4	4	5	4
		Waxes/Asphaltene Oil & with Inj Gas	4	4	3	4	3	4	4	3
		Mechanical Property & Mineralogy	4	4	3	3	3	3	2	2
		Routine and Special Core Analysis	4	4	4	4	3	3	4	4
		Gas Misc/Imm Sec. & Ter Corefloods	4	4	4	4	3	3	4	4
Surface	Reservoir Development	Current Development Stage	4	4	3	3	3	3	4	2
		Current Development Mechanism	4	4	3	3	3	3	N/A	N/A
		EOR Gas (e.g., CO2) Source and Supply	N/A	N/A	3	3	3	3	5	4
		Subsurface Infrastructure	4	4	4	4	3	3	N/A	N/A
	Drilling, Facilities and HSE	HSSE	4	4	3	4	3	3	1	4
		Injectio/Production facilities	5	3	3	4	3	4	5	5
		Gas Separation facilities	5	3	3	4	3	4	5	5
		Facilities CO2/H2S handling Capability	5	3	5	4	4	4	5	5
		Facilities CO2/H2S Injection capability	5	3	5	3	4	4	5	5
		CO2/H2S Breakthrough and Cycling	5	2	5	2	4	4	5	5
		Integrity Management (Corrosion)	5	3	5	3	4	4	4	4
Others	EOR Related Project Objectives Uncertainties	Displacement Efficiency		4		3		3		3
		Vertical Sweep Efficiency		4		3		3		2
		Areal Sweep Efficiency		3		3		3		2
		Recovery factor		4		3		3		3
		CO2 Purity		4		4		4		N/A
		MMP Condition / Reservoir Pressure		5		3		3		5
		Reservoir Property Alteration		5		3		3		4
		Asphaltene Precipitation		4		2		2		2
		Injectivity		5		3		3		3
		Well Design		5		3		3		4
		WAG Benefit		4		3		3		2
		Injection/Production Rates Optimization		4		3		3		2
		Monitoring/Surveillance Plan Design		4		3		3		2
			4.125	3.6875	3.6875	3.625	3.25	3.4375	3.875	3.6875

Table 1. Complexity and uncertainty matrix used in Abu Dhabi Company for Onshore Operations (ADCO) CCUS project screening (all facts and figures in the following figure are non representative and for demonstration purposes only).

As demonstrated by Table 1 above, a site can be characterized with associated risk. A CDM project could therefore be approved within the approved risk characterization limits.

For data collection and characteristics of a dynamic model, we refer to the EU Directive on the geological storage of carbon dioxide, especially Annex I, step2 and the following steps.

We recommend accepting modeling under the modalities and procedures as a tool for predicting behavior of CO_2 in project specific geological formations, and as a basis for risk assessment, taking into account uncertainties. Any change of the monitoring plan should be supported by the results of an updated model. The modeling method used by a project proponent should be agreed by a CCS Working Group under the EB (see also Section 3). The detailed requirements for modeling should be guided by the EU directive for geological formations[11]. We would also suggest that an international system be developed to regularly update the computational models available for modeling CO2 storage. This would be an iterative way of generating and improving risk assessments of possible paths of the injected CO2 plume.

[11] Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide.

2.4. Boundaries

2.4.1 Description of technical issue to be addressed

The spatial boundaries of a CCS project should include all above-ground and underground installations and storage sites as described and mentioned by the subparagraph (e), paragraph 3 of FCCC/CMP/2010/L.10. However, due to the complexity of projects, and taking into account the various aspects of capture, transportation and storage over a long period of time, certain flexibility in setting boundaries is essential. In the early stages of a project, boundaries should include the above-ground facilities, including the capture, transportation, and injection components. This may not be applicable after the capture and injection components of the project cease. Furthermore, the potential migration pathways of the CO_2 plume might show a different behavior than originally projected. Therefore, we support allowing for a dynamic project boundary, which will change over time and project stage.

Draft Decision Paragraph 3

Subparagraph (e): The boundaries of carbon dioxide capture and storage in geological formations shall include all above-ground and underground installations and storage sites, as well as all potential sources of carbon dioxide that can be released into the atmosphere, involved in the capture, treatment, transportation, injection and storage of carbon dioxide, and any potential migratory pathways of the carbon dioxide plume, including a pathway resulting from dissolution of the carbon dioxide in underground water;

Subparagraph (f): The boundaries referred to in paragraph 3 (e) above shall be clearly identified;

This submission does not directly address trans-boundary issues or their resolution under current modalities and procedures. However, it should be in the interest of project owners/project participants to unambiguously clear their project of any trans-boundary-related issues upfront and to demonstrate that trans-boundary issues are not relevant to their specific project's geological formation, taking into account migration of the CO_2 plume, groundwater contamination, and seepage pathways.

2.4.2 Recommendations on addressing boundaries in modalities and procedures

In line with the recommendations set out in the external assessment report for the UNFCCC and in the annotations of EB 50, page 13, we recommend that following elements be incorporated into the CDM modalities and procedures:

1) Sub-surface, any project boundary described within a CCS CDM Approved Methodology would need to include a larger volume than just the storage reservoir so as to include potential secondary containment formations. This larger volume, referred to as a "storage complex," includes the storage site and surrounding geological domains which can have an effect on overall storage integrity and security, and thus be a potential source of anthropogenic emissions.
2) In the event that CO_2 does move out of a predefined determined project spatial boundary, the monitoring plan should be revised and reassessed by the DOE, with the option of changing the spatial boundary to ensure all potential seepage locations are included within the project boundary.
3) The validation of the project boundary requires a DOE with appropriate CCS expertise.

(Source: implication of the Inclusion of Geological Carbon Dioxide Capture and Storage as CDM Project Activity (EB 50, Annotations, Annex 1, page 13)

2.5. Seepage measuring and accounting

2.5.1 Description of technical issue to be addressed

Draft Decision Paragraph 3

Subparagraph (g): Any release of carbon dioxide from the boundaries referred to in paragraph 3 (e) above must be measured and accounted for in the monitoring plans and the reservoir pressure shall be continuously measured and these data must be independently verifiable;

CO_2 Seepage Measurement

Seepage should be monitored and quantified based on one or more of the following techniques:

- Monitoring reservoir properties that can indicate and quantify seepage, including continuous reservoir pressure measurement;
- Reservoir behavior through geological models;
- Monitoring well integrity;
- Shallow (sub)surface monitoring; and
- Atmospheric monitoring;
- Surface movement monitoring using satellite geodetic sensing;
- Permanent geophysical monitoring; and
- Any other technology that becomes available for this purpose.

Geochemical and surface monitoring must be performed in order to measure and account for any CO_2 seepage from the storage. Two of the primary CO_2 seepage monitoring techniques are:

1. Isotopic characterization of CO_2 for monitoring, and

2. Diode laser absorption sensors for continuous CO_2 surface monitoring (for more details see Annex 2).

In case of confirmed significant seepage detection (the definition of which should be agreed during the project permitting approval), CO_2 injection operations should be required to cease. In all cases, detailed investigations should be carried out by the project participant/project operator in order to:

- initiate corrective measures required to restore the storage integrity;
- take reasonable corrective measures to minimize any impact of the seepage on environment, human health and safety; and
- initiate actions to quantify seepage.

2.5.2 Recommendations on addressing seepage and accounting in modalities and procedures

Accounting for CO_2 seepage in monitoring plans

- If seepage occurs during the crediting period, then the amount of seepage emissions should be quantified according to agreed/approved procedures, incorporating the most accurate and current technology, and considering uncertainties in the estimate. An amount equal to the mass of seepage quantified following these procedures should either be deducted from the entitlement for the respective period, or an equivalent amount should be surrendered to the CDM Registry Account.
- If seepage occurs after the end of the crediting period, then the amount of seepage emissions shall be quantified and the equivalent amount of permanent emissions certificates returned to the CDM Registry Account.

3rd party verification

The monitoring plan should account for:

- Data to be collected and properly recorded
- Data to be readily available for 3rd party verification
- Retention period and security for data

Seepage and leakage should be a part of a long term monitoring plan, and subject to regular inspection. The EB may wish to define periodic measurement and reporting and independent inspection reporting guidelines.

Seepage could also be accounted and adjusted for with a buffer CER issuance mechanism and liability allocation.

2.6. Trans-boundary effects

2.6.1 Recommendations on addressing trans-boundary effects in modalities and procedures

We are of the opinion that additional legal complexities will be associated with trans-boundary projects, and therefore such projects can be considered only after more experience is gained with the implementation of CCS projects. Therefore, any project proponent should initially be required to demonstrate that there is no trans-boundary effect associated with their project, until sufficient learning has been acquired to permit the inclusion of trans-boundary projects.

Draft Decision Paragraph 3

Subparagraph (h): The appropriateness of the development of transboundary carbon dioxide capture and storage project activities in geological formations and their implications shall be addressed;

2.7. Accounting of associated project emissions (Leakage)

2.7.1 Recommendations on addressing associated project emissions (Leakage) in modalities and procedures

All project-associated emissions should be calculated and included in an ex-ante estimate at the project design phase and included in the monitoring plan. The monitoring plan should periodically measure and verify actual associated emissions during the project life. This monitoring plan data should be verified by third parties.

Draft Decision Paragraph 3

Subparagraph (i): Any project emissions associated with the deployment of carbon dioxide capture and storage in geological formations shall be accounted for as project or leakage emissions and shall be included in the monitoring plans, including an ex-ante

The project emissions should include as a minimum:

- CO_2 Capture and separation activities
- CO_2 treatment and compression activities
- CO_2 transportation activities
- CO_2 injection activities

2.8. Risk and safety assessment

2.8.1 Description of technical issue to be addressed

Managing the risk of CO_2 injection in a subsurface storage (including existing oil and gas reservoir storage site) requires:

a) Assurance of safe operational integrity and containment of the retained/recycled CO_2 (utilization factor), and
b) Performance of dynamic risk management and mitigation (DRMM) to ensure risks and uncertainties are effectively managed throughout the project life-cycle.

Uncertainty can be analyzed and quantified, and if managed properly, reservoir development and risk mitigation can be improved as a result. Consequently, reservoir management, CO_2 injection, process physics, chemistry and ultimately modeling is essential to developing a risk assessment matrix correlated with a mitigation plan (see Table 2 below).

Significant capital expenditure and manpower are required to conduct these highly technical and state-of-the-art studies to address uncertainties as described below (conducted by Abu Dhabi National Oil Company).

Draft Decision Paragraph 3

Subparagraph (j): A thorough risk and safety assessment using a methodology specified in the modalities and procedures, as well as a comprehensive socio-environmental impacts assessment, shall be undertaken by independent entity(ies) prior to the deployment of carbon dioxide capture and storage in geological formations;

Subparagraph (k): The risk and safety assessment referred to in paragraph 3 (j) above shall include, inter alia, the assessment of risk and proposal of mitigation actions related to emissions from injection points, emissions from above-ground and underground installations and reservoirs, seepage, lateral flows, migrating plumes, including carbon dioxide dissolved in aqueous medium migrating outside the project boundary, massive and catastrophic release of stored carbon dioxide, and impacts on human health and ecosystems, as well as an assessment of the consequences of such a release for the climate;

Subparagraph (l): The results of the risk and safety assessment, as well as the socioenvironmental impacts assessment, referred to in paragraphs 3 (j) and (k) above shall be considered when assessing the technical and environmental viability of carbon dioxide capture and storage in

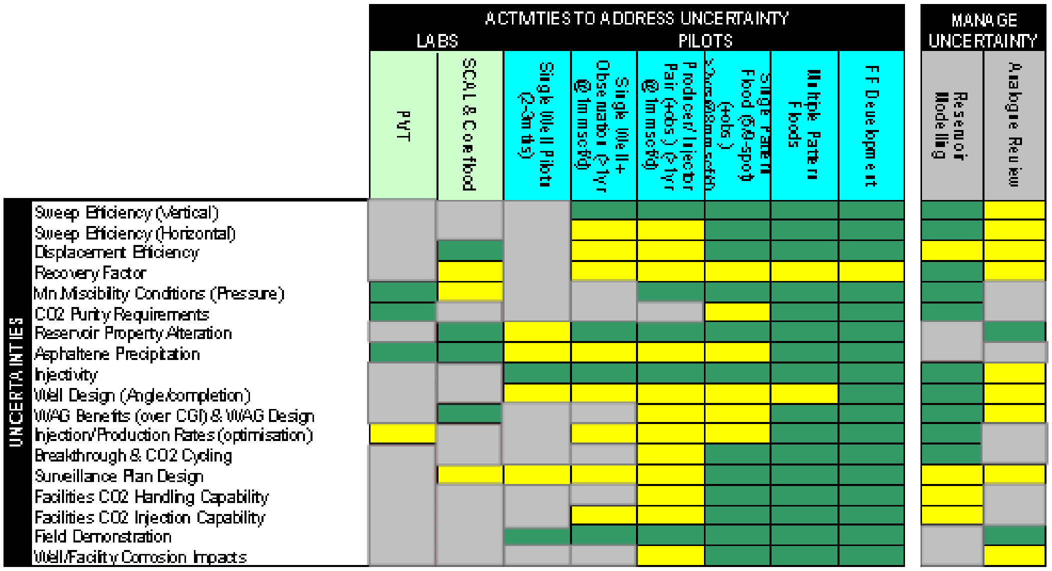

Table 2. List of key CO_2 CCUS related uncertainties and mitigations considered for Abu Dhabi CCUS project

Analytical solutions permit rapid sampling of the uncertainty across all input parameters, and thus more robust risk assessment. This principle has been used recently to perform uncertainty quantification of seepage through hundreds of wells across several geologic layers [Nordbotten et al., 2009]. For each geologic basin, the risk assessment methodology should be broken down into four subtasks: (1) Sensitivity analysis on model parameters; (2) determination of probability distributions for parameters with greatest impacts; (3) uncertainty quantification; and (4) estimates of risk of CO_2 seepage. These simplified, quick, analytical forward models will also be instrumental in the design of monitoring techniques, as they provide first-order estimates of pressure evolution and CO_2 plume footprint.

2.8.2 Recommendations on addressing risk and safety assessment in modalities and procedures

Project proponents should be required to perform Health, Safety, and Environmental Impact Assessment Studies (HSEIA), commensurate with the project phase, through an independent qualified entity.

A "Terms of Reference" document outlining the HSEIA scope, objectives and methodology consistent with the CDM modalities and procedure requirement should also be submitted and approved by the local authorities and the CDM designated authority prior to performing the work.

HSEIA studies should use a probabilistic risk assessment methodology, and the HSEIAA study scope should cover the entire project boundary. The risk approach as proposed in the CO2QUALSTORE and CO2PIPETRANS Guidelines provide a good practice tool to ensure risks and uncertainties are effectively managed throughout a project's life-cycle.

Finally, risk and impact assessment outcomes should be reviewed by national authorities and the results should be reported to the Host country DNA.

2.9 Liability under the CDM scheme

2.9.1 Recommendation for the inclusion of liabilities under the CDM scheme into the modalities and procedures

Initially, all liability related to the project should rest with the project proponent, throughout the project life cycle and up until proper storage closure has been demonstrated.

The long term liability for the storage site should be transferred to the host country, either through national regulation or a negotiated agreement specific to the project.

Such long term liability schemes should be finalized during the project permitting stage and should address the conditions for transfer and the financial mechanism for meeting the liabilities.

Draft Decision Paragraph 3

Subparagraph (m): Short-, medium- and long-term liability for potential physical leakage or seepage of stored carbon dioxide, potential induced seismicity or geological instability or any other potential damage to the environment, property or public health attributable to the clean development mechanism project activity during and beyond the crediting period, including the clear identification of liable entities, shall:

i. Be defined prior to the approval of carbon dioxide capture and storage in geological formations as clean development mechanism project activities;

ii. Be applied during and beyond the crediting period;

iii. Be consistent with the Kyoto Protocol;

Subparagraph (n): When determining the liability provisions referred to in paragraph 3 (m) above, the following issues shall be considered:

i. A means of redress for Parties, communities, private-sector entities and individuals affected by the release of stored carbon dioxide from carbon dioxide capture and storage project activities under the clean development mechanism;

ii. Provisions to allocate liability among entities that share the same reservoir, including if disagreements arise;

iii. Possible transfer of liability at the end of the crediting period or at any other time;

iv. State liability, recognizing the need to afford redress taking into account the longevity of liabilities surrounding potential physical leakage or seepage of stored carbon dioxide, potential induced seismicity or geological instability or any other potential damage to the environment, property or public health attributable to the clean development mechanism project activity during and beyond the crediting period;

3 Provision for restoration of potential damages to ecosystems

3.1 Recommendation for the inclusion of provisions for restoration of potential damages to ecosystems into the modalities and procedures

There is a limit on the period of time over which project proponents will have responsibility for the liability associated with the CO_2 storage, since their lifetime is limited compared to the time-frame long term CO_2 storage requires.

Draft Decision Paragraph 3

Subparagraph (o): Adequate provision for restoration of damaged ecosystems and full compensation for affected communities in the event of a release of carbon dioxide from the deployment of carbon dioxide capture and storage in geological formations must be established prior to any deployment of

Project proponents should therefore make financial provisions to address any potential damage to the environment, human health and properties beyond the period of their direct short term liability. This financial provision should be transferred to an authorized body designated by the host country after the end of their short term liability period.

The financial provision covering the long term liability should be based on a long term probabilistic risk assessment, to be approved by the local authorities as per agreed international rules.

The liability transfer from the project proponent to the host country should be materialized by a bilateral agreement which sets the period of liability and conditions to consider the CO_2 storage as permanent. Host countries should accept the principal of transfer of liability during the initial stages of the project approvals and make sure that all technical and CDM issues are addressed before giving their approval.

The UAE supports the development of comprehensive environmental impact statements (EIS) for CCS projects, and believes that that the scope of an EIS for a CCS project should be expanded to include a compositional analysis of the CO2 stream and public participation.

3. Changes in roles and administrative procedures under the a new CCS Scheme

In addition to the recommendations already described in the previous chapter, we support the inclusion of following elements to the Modalities and Procedures.

3 .1. General administrative changes

Technical Committee/CCS Working Group

Most of the issues described above lead to a set of new modalities and procedure for carbon dioxide capture and storage in geological formations as clean development mechanism project activities. CCS activities encompass a complex set of technical, geological, legal requirements, as well as socio-environmental, modeling, hazard and safety aspects. This set of complex requirements have not had to be addressed in CDM projects so far. Expertise spanning across all these topics will therefore be required to ensure informed approval or rejection of methodologies for CCS, as well as for reviewing projects for CDM approval. We believe that the Executive Board needs the support from a CCS Working Group, similar to the Afforestation and Reforestation Working Group (ARWG). Like the ARWG, the mandate of the CCS Working Group would be to prepare recommendations in cooperation with the Methodologies Panel on submitted proposals for new baseline and monitoring methodologies for CDM CCS projects.

Additional to this task, the CCS Working Group should support the Registration and Issuance Team (RIT) and with it, the Executive Board in their CCS-CDM project activity appraisal.

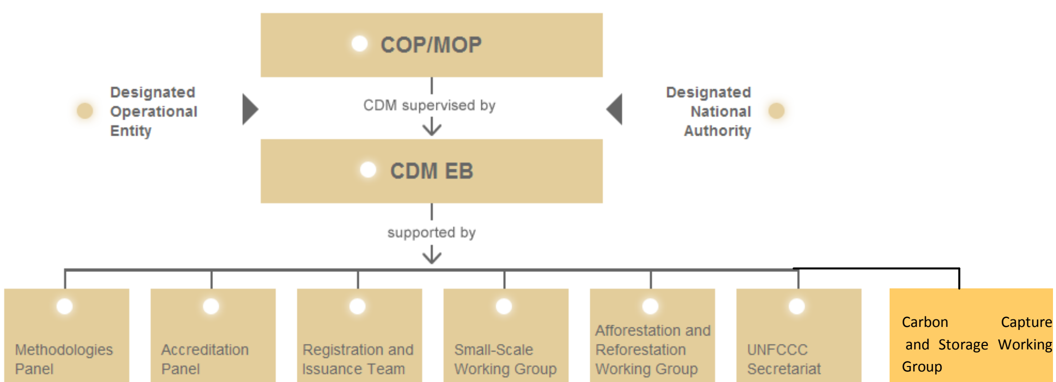

Fig. 3: Governance for CCS in CDM

Compliance and Compensation Fund

We would also recommend the establishment of a Compliance and Compensation Fund. This could be similar to approaches in the mining industry, and/or to the International Fund for Compensation of Oil Pollution Damage. It would also be in line with the already existing

Adaptation Fund, which was established to finance adaptation projects and programmes in developing country Parties to the Kyoto Protocol that are particularly vulnerable to the adverse effects of climate change. The Adaptation Fund is financed by a 2% levy on CERs issued by the CDM. Similar to the financial setup of the Adaptation Fund, a percentage levy on the CERs issued by the CDM from CCS projects should flow to this Compliance and Compensation Fund. The objectives for the compensation fund could be as follows:

- Covering accidents and compensating for any damage caused to the people and the environment as a result of CCS CDM projects;
- Monitoring and corrective actions, especially to cover long term liabilities in least developed countries associated with CCS CDM projects; and
- Covering seepage emissions and the release of carbon dioxide to the atmosphere from CCS CDM projects.

The establishment of the Compliance and Compensation Fund requires further elaboration, but the UAE expresses its support for the creation of such a Fund in principle.

3 .2. Roles of the Conference of the Parties

All provisions of section B of the CDM modalities and procedures, contained in the annex to decision 17/CP.7, should apply *mutatis mutandis* to carbon dioxide capture and storage in geological formations project activities under CDM. In addition, we recommend including the following aspects in the modalities and procedures:

- Assist in setting up a long-term compliance fund for CCS projects.
- Assist in setting up a CCS Working Group to support the EB in its appraisal procedures for methodologies and projects.
- Include carbon capture and storage in geological formations as a new sectoral scope (16).

3 .3. Roles of the Executive Board

All provisions of section C of the CDM modalities and procedures, contained in the annex to the decision 17/CP.7, should apply *mutatis mutandis* to carbon dioxide capture and storage in geological formations project activities under CDM. In addition, we recommend including following aspects in the modalities and procedures:

- Establish, develop and maintain a compensation fund, covering accidents, seepage avoidance, monitoring and corrective actions for long term risk mitigation and correction actions in least developed countries.

- Risk assessment and mitigation measures, including emergency response plans, should not be considered as proprietary or confidential.
- Establish and support the CCS Working Group.

3 .4. Participation requirements

All provisions of section F of the CDM modalities and procedures, contained in the annex to the decision 17/CP.7, should apply *mutatis mutandis* to carbon dioxide capture and storage in geological formations project activities under CDM. In addition, we recommend including following aspects into the modalities and procedures:

- A party not included in Annex I may host a carbon dioxide carbon capture and storage in geological formations as CDM project activity if the host country has designated these sites as potential storage sites and has undertaken an assessment of the storage capacity of their territory.
- The long term liability for the storage site has been evaluated by the host country; either national regulation is in place taking into account long term liability after post closure, or the project participant has an agreement in place with the host country clearly resolving liability.

3 .5. Roles of the DOE

All provisions of section E of the CDM modalities and procedures, contained in the annex to the decision 17/CP.7, should apply *mutatis mutandis* to carbon dioxide capture and storage in geological formations project activities under CDM. In addition, we recommend including following aspects in the modalities and procedures:

- Validation and verification services for carbon capture and storage projects require a complex validation/verification team, covering all areas of CCS-specific knowledge, such as geological, modeling, risk assessment, and HSEIA expertise.

3 .6. Validation and verification services

All provisions of section F of the CDM modalities and procedures, contained in the annex to the decision 17/CP.7, should *mutatis mutandis* to carbon dioxide capture and storage in geological formations project activities under CDM. In addition we recommend the consideration of following aspects into the modalities and procedures:

- Project participants should be required to submit documentation on the procedure and selection of the geological formation as carbon storage site to the Designated Operational Entity (DOE). The criteria should include “(1) adequate capacity and injectivity, (2) a satisfactory sealing caprock or confining unit, and (3) a sufficient stable geological environment to avoid compromising the integrity of the storage site[12]. Storage sites which consist of basins that (1) are thin (≤1000m), (2) have poor reservoir and seal relationships, (3) are highly faulted and fractured, (4) are within fold belts, (5) have strongly discordant sequences, (6) have undergone significant diagenesis or (7) have "overpressured reservoirs" (IPCC – Special report on carbon dioxide capture and storage) should be excluded. The project participant should follow state of the art selection procedures as per guidance set out by national or international standards or legislation.

- The crediting period should begin at the start of injection into the reservoir. We propose would propose the use of a renewable crediting period of 10 years, which might be renewed. The EB should come to a decision, with support from the CCS Working Group, on a maximum number of years for crediting.

3 .7. Project Design Document for carbon capture and storage in geological formations

Similar to the Project Design Document (PDD) under CDM, a CCS project participant should have to describe section A – E. In addition, we recommend the following points to be addressed by the project participant:

- A description of the site selection procedure;
- A description of risk assessment and modeling conducted, including a risk mitigation plan;
- The exclusion of trans-boundary issues;
- A description of how national and/or sectoral policies and circumstances have been taken into account, and especially how liability for short term, medium term and long term is addressed;
- Calculations, including a description of how uncertainties have been addressed:
  - using modeling as a support;
  - based on pre-monitoring details;
  - including likelihood of seepage.
- Socio-environmental impacts of the project;
- Risk and safety assessment and a plan for risk mitigation.

During the validation the Designated Operational Entity shall ensure that following documents are provided:

- Evaluation Permit

[12] IPCC Special Report on Carbon dioxide Capture and Storage, 2006, chapter 5: underground geological storage, page 213ff.

- Storage permit
- Operation Permit
- Emergency Response Plan
- Risk Assessment and Mitigation Plan
- Agreement on liability with the national authority
- Monitoring Plan

References:

[1] International Energy Agency: World Energy Outlook 2010.

[2] International Energy Agency: Energy Poverty Report.

[3] The Future of Coal – an interdisciplinary MIT study / Options for a constrained World, Massachusetts Institute of Technology, 2007.

[4] Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide.

[5] IPCC Special Report on Carbon Dioxide Capture and Storage.

[6] IPCC Guidelines for National Greenhouse Gas Inventories 2006.

[7] Srivastava, R. D. (coordinating lead author) (2009). Best Practices for Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geological Formations. U.S. Department of Energy, National Energy Technology Laboratory. www.netl.doe.gov/technologies/carbon_seq/refshelf/MVA_Document.pdf.

[8] Implications of the Inclusion of Geological Carbon Dioxide Capture and Storage as CDM Project Activities, http://cdm.unfccc.int/EB/050/eb50annagan1.pdf.

[9] CO2QUALSTORE – Guideline for Selection and Qualification of Sites and Projects for Geological Storage of CO_2, DNV, 2010; http://www.dnv.com/binaries/CO2QUALSTORE_guideline_tcm4-412142.pdf

[10] CO2PIPETRANS - Recommended Practice for Design and Operation of CO_2 pipelines – JIP CO2PIPETRANS Phase 1 (2008-2009), DNV.

Annex 1: Monitoring in combination with modeling as performed by ADNOC

The procedure linking observations and models will be an ensemble data assimilation algorithm that will use the models to generate a set of possible system descriptions, all consistent with observations. This makes it possible to provide a cost-benefit analysis of the importance of different data types, as well as to design robust operating and monitoring strategies that can work well over a range of conditions.

Data Assimilation and Monitoring Design

Mathematical modeling of the subsurface environment provides a useful way to assess candidate sites for carbon storage and to design effective carbon sequestration strategies. In particular, different sites and operating alternatives can be analyzed by varying the model inputs that characterize the target reservoir, as well as control variables, such as injection well locations, depths, and injection rates. This is a classical application of modeling technology that relies strongly on having access to a physically realistic model. Here we consider two other important modeling applications that are particularly relevant to the UAE CCS project: (a) using models to merge and interpret data (a process often called "data assimilation"), and (b) using models and data together to design cost-effective real-time monitoring strategies. To understand how models relate to data assimilation and monitoring it is necessary to briefly consider why we should integrate modeling and data collection activities in a CCUS monitoring program.

In the absence of a predictive model, monitoring is the only way to assess the performance of a carbon sequestration project. The disadvantage of a monitoring-only approach to performance assessment is that we are using the real world as a laboratory. If a sequestration strategy works well this is fine but, if it does not, the consequences could be undesirable and difficult to correct. That is why we use models (and small-scale lab and field experiments) to predict performance in advance. By trying out different alternatives in a controlled modeling experiment we can find designs that are likely to meet project specifications.

The subsurface models we use to identify promising sequestration strategies, however, do not have complete information on geological structure, flow properties, and other relevant environmental variables. If we had a fully predictive model, there would be no need to monitor performance because we would know the outcome with certainty. The real-world needs of the UAE CCUS project require a balance between the extremes of relying only on monitoring and relying only on modeling. We can construct models that give us useful information about the likely performance of a candidate reservoir but we also need to monitor since the model predictions are not certain. The most realistic and scientifically defensible approach to performance assessment of CO_2 sequestration is to integrate modeling and monitoring.

We will follow such an integrated approach here. First, we will develop data assimilation procedures (or work flows) that use models to combine measurements for performance assessment. Then we will expand these procedures to include a real-time monitoring design capability. Real-time design enables the CO_2 monitoring program to evolve as new measurements become available, using models that are continually updated. In both cases we will use models developed in other project tasks so that assumptions and results are consistent across the project. This integrated approach to monitoring and operations has a long and successful history in meteorology, where complex mathematical models are routinely used to merge (or assimilate) diverse measurements for forecasting and also to design “adaptive observation” programs.

Here, we will build on our experience with data assimilation and monitoring methods in meteorology, hydrology, and, most important, petroleum engineering [Moore and McLaughlin, 1978; Graham and McLaughlin, 1989; McLaughlin et al., 1993; McLaughlin, 2002; 2007; Zhou et al., 2006]. Over the past several years we have contributed to the growing field of real-time petroleum reservoir management by developing modeling, estimation, and control strategies to make best use of observations collected before and during secondary recovery operations [Jafarpour and McLaughlin, 2008, 2009, 2009a]. This work provides an excellent basis and starting point for a focused design of the monitoring program.

Of particular interest for this project are the following types of measurements:

a) Fluid pressures, fluxes, and composition in injection and a limited number of monitoring wells;

b) Active seismic measurements ranging from cross-well to VSP to 4-D surface seismics;

c) Passive seismic measurements, including measurements that rely on induced seismicity;

d) Geodetic measurements, including data from (existing or newly deployed) GPS stations and InSAR surveys;

e) Time-lapse microgravity and/or gradiometry measurements;

f) Electrical resistance tomography;

g) Geochemical and surface monitoring of atmospheric CO_2 concentrations.

These measurements represent a suite of possible sensing technologies that we intend to investigate for this particular application. Some of these may prove to be technically inappropriate or too expensive for the conditions at the UAE. An assessment of the most promising sensing technologies will be an ongoing task of our project, carried out as performance and cost data become available.

Fluid Flow Modeling

The fundamental objective of CO_2 sequestration operation is to maximize the overall amount of injected CO_2, while minimizing the risk of leakage. Safe, long-term sequestration of supercritical CO_2 in such large-scale aquifers is expected to be achieved through the objective of mechanisms of capillary, solubility, and mineral trapping. These mechanisms occur over a wide range of time scales, ranging from years to millennia. Capillary, solubility, and mineral trapping represent increasingly higher levels of CO_2 storage security. Because of the relatively long time scales required to trap, or immobilize, the CO_2, an impermeable caprock is needed to prevent the undissolved super-critical CO_2, which is buoyant and highly mobile with respect the resident brine, from leaking to shallower formations (e.g., fresh water aquifers), or to the atmosphere.

The total amount of CO_2 that can be sequestered in an aquifer is primarily a function of the rate at which CO_2 is immobilized by the different trapping mechanisms, as well as, the geologic `quality' of the aquifer based on its overall size, permeability characteristics, the relative impermeability of the caprock, and the absence of major geologic faults and fractures. The longer that the injected CO_2 remains in contact with the caprock (due to its buoyant supercritical state with respect to the resident fluid), the greater the risk of CO_2 leakage. Vertical and up-dip migration of large-scale CO_2 plumes over long periods of time also adds to the risk of leakage. Moreover, changes in the pressure field due to injection of large amounts of CO_2 may lead to the activation, or creation, of fractures and faults that provide CO_2 leakage pathways beyond the target formation.

In order to plan, execute, and monitor field-scale CO_2 sequestration operations, accurate modeling of the physical and chemical processes that govern solubility, capillary, and mineral trapping in subsurface geologic formations is necessary. For that purpose, the complex dynamics associated with the various trapping mechanisms and their interactions must be analyzed in detail and modeled accurately. That is, the governing equations must be formulated rigorously, and the length and time scales that govern the physical and chemical processes associated with subsurface CO_2 sequestration must be resolved adequately. Then, using a detailed characterization model for the specific storage target, high-resolution numerical simulation can be used to make quantitative predictions of the complex dynamics associated with field-scale CO_2 sequestration operations. The simulation capability must be able to cover the (relatively short) injection and the (much longer) post-injection periods.

The dynamics of multiphase flow and transport in large-scale heterogeneous geologic formations, which describe the complex solubility and capillary trapping processes rigorously, must be modeled accurately in order to obtain reliable predictions of the fate of the injected CO_2. The computed spatial and temporal distributions of the flow (pressure, velocity) and transport (saturations and concentrations) provide predictions of the overall effective storage capacity (related to volumetric `sweep' efficiency), migration distances of mobile CO_2 plumes, and assessment of capillary (residual) and solubility trapping. Such a simulation based approach is necessary to plan, execute, and monitor field-scale CO_2 sequestration projects.

Geomechanical Processes and Caprock Integrity

The interaction between the pore fluids and the rock is an essential component in the assessment of CO_2 storage in geologic formations. Thus, geomechanical studies provide critical input data for reservoir design and management. Injecting large volumes of carbon dioxide will create a pore-fluid that, at least initially, will disturb both the local mechanical and chemical equilibrium of pore fluid and the surrounding reservoir and cap rocks. The pressurization of the formation upon injection of supercritical CO_2 will reduce the effective stress in the rock. This process can have several effects that need to be evaluated, including the displacement of brine, the activation of dormant faults that can then serve as leakage pathways, and the creation of fractures that may compromise the integrity of the caprock. In addition to understanding these mechanical effects, both the short- and long-term reliability and stability of the repository demands detailed knowledge of chemical effects associated with the disturbance in chemical equilibrium. The kinetics of the interactions between the fluid and minerals [Emberley et al., 2004], and the effects of the fluid/rock interactions on the mechanical and transport properties of the reservoir and cap rock [Shukla et al., 2010] must be determined. A combination of theoretical, computational, and laboratory work to evaluate chemo/geomechanical processes and seal integrity in the target deep aquifers are needed. The knowledge of the regional state of stress, which is largely uncertain but can be inferred from oriented cores, minifrac tests, etc. are essential for model calibration.

Coupling Geomechanical and Fluid Flow Modeling

The interactions between the flow dynamics and geomechanical deformation must also be quantified in order to make predictions of large-scale subsurface CO_2 sequestration operations. Given that very large amounts of CO_2 must be injected into the host geologic formation (i.e., deep saline aquifer), we have to understand the complex interactions between the flow dynamics (e.g., pressure field and plume migration) and the stress and strain fields in and around the storage formation. Such interactions have been shown to affect the flow properties of the reservoir, including the porosity and permeability. More importantly, for large-scale sequestration operations, there is a major concern of activating, or even inducing, fractures that may provide pathways for the CO_2 to leak into shallower formations, or possibly all the way to the surface. Thus, reliable and computationally efficient methods the can describe the complex coupling between the flow dynamics and geomechanical deformation are needed.

To reiterate, quantification of the state of deformation and stress of the reservoir is essential for the correct prediction of a number of processes critical to geologic CO_2 storage, including pressure evolution, surface subsidence, seal integrity, hydro fracturing, and induced seismicity; therefore, a central aspect is the development of computational models for the simulation of coupled flow and geomechanics, which allows studying the state of stress at depth, caprock integrity and faulting activation upon CO_2 injection, with application to individual selected formations. The theoretical developments based on chemo-mechanics laboratory experiments that will test the interplay between CO_2 dissolution, rock strength, flow properties, and compaction for actual carbonate reservoir rock and caprock. The experiments will inform the computational models and will lead to an integrated assessment of caprock integrity, which will identify not only the potential for leakage risk, but also which leakage pathway is most likely (e.g., well leakage, sandy caprock, fractured caprock, or active faults).

The key to the successful implementation of above modeling approach is the use of an integrated multi-disciplinary team which can leverage the vast experience gained in ADNOC of dealing with subsurface uncertainty. The whole approach is transparent and allows the reviewers to appreciate and challenge the assumptions/inputs.

Annex 2: Examples for CO_2 seepage monitoring

I. Isotopic Characterization of CO_2 for Monitoring

CO_2 is a ubiquitous compound that is in the atmosphere, water and soil. CO_2 concentrations change both spatially and temporally. The causes of changes could be natural and/or due to human activity (e.g. increased vehicular traffic). An important aspect of monitoring is to determine whether any change in surface concentration is due to possible leakage from the sequestered CO_2. This determination requires "foolproof" tracers that would work in a CO_2 rich environment.

The recommended geochemical tracers are cluster isotopes - long chains made of different isotopes of carbon and oxygen. These compounds are formed during the combustion process. They contain the "DNA" signatures of every batch of CO_2 produced. The concentrations of a subset of these isotopes in the atmosphere are extremely low. Because of the low background they are extremely sensitive to small changes.

For monitoring with isotopic tracers, the isotopic signature of the CO_2 being injected is determined. Then, periodically or whenever an escape is suspected, air and soil samples are tested to determine whether they contain any CO_2 bearing the isotopic signatures of the injected CO_2.

II. Diode Laser Absorption Sensors for Continuous CO_2 Surface Monitoring

In addition to the proposed wide spectrum of subsurface CO_2 monitoring, another approach would be to develop a new approach for continuous CO_2 detection at the surface. The monitored surface of the storage reservoir can be 10's to 100's of square kilometers and the use of fixed and/or mobile gas analysis detectors to continuously monitor the CO_2 concentration is far from practical. In contrast, laser beams that can travel several kilometers without losing their coherence and can therefore scan large surface areas. By choosing an appropriate wavelength, detection scheme, and inversion technique, the concentration and location of a chemical species can be determined. The work proposed in this task aims at developing diode laser absorption techniques for continuous CO_2 surface leak detection.

Laser based methods (such as laser-Raman scattering radar) for the remote detection of atmospheric pollutants have been studied and used since the early seventies [Hildal and Byer, 1971; Inaba and Kobayasi, 1972]. Although these early techniques are still in use today for vertical distribution of gases in the troposphere and stratosphere, they have not been adopted for ground surface scanning and detection. In addition, these systems are bulky and very expensive. Infra red (IR) Diode laser based techniques—developed in the 80's and 90's and found broad use in industrial and environmental applications—are smaller and less expensive [Allen, 1998; Webber et al., 2000; Martin, 2002]. The use of IR laser absorption spectroscopy was initially restricted to laboratory experiments on chemical kinetics, especially in the field of combustion and plasma processes [Sassi, 1999]. But since the late nineties there has been a rapid expansion towards its use in more applied areas such as atmospheric and pollution monitoring as well as process monitoring and control. These advances have largely benefited from improvements in laser technology and associated electro-optics deriving from applications in the telecommunications and consumer electronics industries. In addition, there has been an increased interest in direct species and parameter measurements in the atmosphere and in the environment in general.

In laser absorption measurement the narrow band laser beam is wavelength tuned across a much broader molecular absorption line and the change in the detected-transmitted laser power is measured (Figure 4). At known temperature and pressure, among other experimental parameters, this power change is proportional to the absorbing species concentration along the path length of the laser beam. Spatially resolved absolute concentrations can be obtained using tomographic inversion methods. The technique can be used to simultaneously monitor several species with high spatial and temporal resolutions. In addition to their widespread use and low cost, IR diode lasers can be used with fiber optic technology and inexpensive spectrometry components to build large emitter/sensor networks that can scan very large areas. Recently, this technique has been used for in situ sensing of atmospheric CO_2 with laser diodes emitting near 2.05 micrometers in laboratory experiments. A compact version of this technology has been adopted for the European campaign of atmospheric measurements [Zeninari et al., 2004]. Recently, it has become possible to measure field-scale isotopic CO_2 with tunable diode laser absorption spectroscopy for stable isotope studies of ecosystem-atmosphere CO_2 exchange [Bowling et al., 2003].

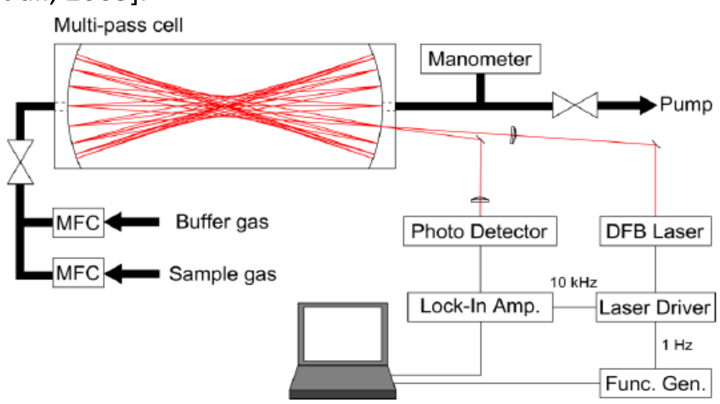

Figure 4: Laboratory diode laser absorption apparatus for species detection [Asakawa et al., 2010].

MIT work on laser diagnostics techniques [Sassi, 1999], and the commercial availability of IR diode lasers in addition to all the emission and detection optical components, might provide confidence that an effective network of diode laser absorption sensors for continuous CO_2 leak detection can be deployed over large areas.