State-of-the-Art review of Directives and Regulatory Regimes Related to Operational and Safety Risks

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Action on CO_2 Geological Storage

CO_2GeoNet
The European Network of Excellence
on the Geological Storage of CO_2

CGS Europe Key Report

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PREFACE

This report is the result of a joint effort carried out by various members of the CGS Europe project (www.cgseurope.net) - the "Pan-European Coordination Action on CO_2 Geological Storage", funded within the 7th framework programme of the EU. The report is based on current literature Directives and Regulatory Regimes Related to Operational and Safety Risks. It focuses on Europe and the EU CCS and Emission Trading Directives, as well as international regulations and closely follows their definitions and terminology.

The report is not a monograph, but rather an edited compendium of contributions from individual network partners. Hence, chapters and sections may vary in style and level of detail. The authors gratefully acknowledge the various CGS Europe partners who participated in reviewing the draft and the resulting fruitful discussions.

The report is public so that any interested party can readily make use of it. CGS Europe does not claim completeness, nor comprehensive consideration of all legal or regulatory requirements on operational and safety risks in Europe.

The authors hope that this report will provide concise and ultimately helpful information to various stakeholder groups including scientists, competent authorities, operators and regulators. The reader is expected to have some basic understanding of CO_2 geological storage and related technologies.

EXECUTIVE SUMMARY

CO_2 Capture and Storage (CCS) is recognised as a potentially important corner stone amongst the climate change mitigation technologies in Europe and worldwide. Although individual components of the CCS value chain are proven technologies, as a whole-chain process, CCS is a new technology which was expected to reach fast implementation and at a very large scale in the energy and other industrial sectors. The concern that a rapid implementation could result in a regulatory vacuum, lead the European Commission, the USEPA and other international organisations to proactively work on relevant legislation and directives. Legislation specifically and CO_2 geological storage was also implemented at national and regional level in several regions of the world. This legal context forms the focus of this report, but is approached from the practical point in which the storage project and the related operational and safety risks are the starting point.

At time of publication, nearly all EU members have used the EU CCS Directive to implement appropriate legislation that allows the safe and uniform rollout of CCS throughout Europe, especially regarding the geological storage of CO_2. Although implementation of the specific regulation is mandatory, member states can autonomously decide whether or not to allow CCS activities on their territory.

Geological storage of CO_2 deserves specific attention, and is as such also the focus of this report. This key report is at the same time a highly practical and scientifically sound document, that provides a thorough overview of the legislation and regulation in place in Europe, and compare it with that of other leading CCS countries and regions.

Rather than taking the structure of a legal document as starting point, this report approaches this topic from the following five, very practical angles:

- Storage site operation
- Leakage events
- Monitoring
- Remediation
- Closure and post-closure

These form the main chapters of this report, and care was taken that each of them can be read largely independently from the others, allowing the reader to approach the topic from the angle that is best suited to them.

CO_2 Storage Site Operation Risks and Regulations (Chapter 2)

This chapter identifies the risks related to the injection phase during CO_2 geological storage and summarises the national, European and international legislation of CO_2 geological storage and CCS-related legislations. The materials presented provide an overview of the risks arising during the CO_2 storage operation phase. Risks are described with regards to their spatial extent and significance: local environmental risks, general operational risk, risks related to CO_2 stream composition, pressure and temperature.

The directives and regulations relating to CO_2 storage site operation are discussed with a special focus on dedicated CCS legislations at international, European and national levels where available. Besides the CCS specific regulations, the EU Emission Trading Directive, the International Climate Change Legislation and Clean Development Mechanisms and their relations to CO_2 storage site operation phase is considered.

Next, the directives and regulations relating to offshore and onshore CO_2 storage site operation are presented, followed by brief conclusions.

CO_2 leakage risks and related guidelines (Chapter 3)

This chapter presents an overview of the international regulations and guidelines related to potential leakage events of CO_2 from a geological storage site, an overview of the international regulations and guidelines related to leakage, as well as the effects of CO_2 reaching the biosphere.

The chapter starts with a review of the main international acts and agreements that regulate the risk of CO_2 leakage, the London Convention and Protocol, OSPAR, EU Directives on Geological Storage of CO_2 and ETS. These international agreements were elaborated at different times and differ mostly on their focus (e.g. OSPAR focuses only on the effects of CO_2 leakage in the marine environment whereas EU Directive on Geological Storage of CO_2 refers to CO_2 leakage in all environments) and geographical coverage (although they overlap to some extent with regards to this). Still, all regulations require that storage operations are conducted in a safe manner, taking corrective measures in case of leakage. For this reason, they also stipulate the necessity of conducting a thorough risk assessment at each step of a storage project (starting with the pre-operational phase) in order to prevent and mitigate the identified hazards.

In this context, another important part of the chapter refers to guidelines for risk assessment, especially the ones developed under OSPAR (FRAM) and EU CCS Directive (Guidance Document 1). These guidelines comprise several stages for risk assessment, covering the entire cycle of a CO_2 storage project, starting from site characterisation to risk management (including monitoring and corrective measures).

A first step in the risk assessment for a CO_2 geological storage site is to identify all of the potential risks related to the site, especially the potential leakage pathways, presented within this chapter, such as permeable caprock, faults and fractures, wells and other anthropogenic pathways (e.g. hydraulic fracturing of reservoir possibly connected to a CO_2 storage site or extension of fractures to the CO_2 storage complex).

The final part of the chapter presents the effects of a potential CO_2 leakage on the environment and on human safety and health through a few studies made on this topic using natural analogues (e.g. Laacher See, Germany; Panarea Island, Italy) and some incidents and regulations related to human and animal exposure to increased levels of CO_2. Although the exact effects of a CO_2 leakage are not yet known (as the composition of CO_2 stream and the re-actions of co-injected elements play an important role in this issue and there is still a research need for controlled CO_2 leakage), it is commonly accepted that CO_2 leakage can cause acidification of sea or groundwater, mobilisation of toxic elements (due to pH change in soils), adverse effects on plants, animals and humans.

Directives and regulations related to storage site monitoring (Chapter 4)

This chapter provides an overview how monitoring is addressed in legislation and directives, how guidelines and protocols have been developed to interpret the legislation and how some of the early integrated industrial scale CCS projects have incorporated monitoring plans in their permit applications.

Legislative regimes of EU, US, Canada and Australia were reviewed. The focus was on EU legislation and its CCS Directive and ETS Directive. The associated Guidance Documents and ETS-MRG guidelines provide more practical information on how to translate legislative monitoring requirements to a practical implementation and what role should monitoring play in case that leakage occurs. The high level content concerning monitoring of various international documents such as OSPAR, the London Convention, the IEA-MRF, CO2QUALSTORE as well as the IPCC Special Report and its Guidelines have been incorporated in many regulatory regimes, including the EU CCS Directive. The EU and Australia can be considered the leading players in establishing CCS related regulation frameworks, closely followed by the US and Canada.

A comparison of regulatory documents from different jurisdictions showed, that the objectives for monitoring are similar in terms of tracking the injected fluid in the subsurface and to monitor key risks related to HSE. Further common principles are that monitoring plans should be risk and objectives based, site specific and non-prescriptive in terms of technologies applied. While the EU regulation is entirely focused on emissions reduction objectives, the USA regulation seems more focused on enhanced oil production (EOR) and so called CCUS (carbon capture, use and storage). Moreover, EU legislation requires permanency of stored CO_2, while the US (and Canadian) legislation seem to accentuate stronger the utilisation of injected CO_2. In all cases long-term liability provisions need further revision and consolidation. Regular reporting of the results of monitoring to a competent authority is always requested. It will be crucial that the performance quality and the relevancy of specific operational procedures and/or corrective measures taken are inspected by a competent authority. However, minimum competency requirements for the verifier are not defined in the CCS Directive. It may be worth considering the introduction of an accreditation procedure for verifiers under the CCS Directive at different levels (national, international).

Some examples of integrated industrial scale projects implementing monitoring plans in their permit applications have been evaluated in this document. Information has been taken from published FEED studies as well as from storage permit applications. As one might expect, major differences exist between onshore storage (e.g. the Quest project in Canada) and offshore storage (e.g. the ROAD project in the Netherlands).Though differences can clearly be identified, all examples follow a similar risk-based approach for defining the monitoring plan. In all cases, wells were identified as potential hazards, either in terms of potential CO_2 leakage along the wellbore, or induced brine migration by the elevated pressures in the reservoir. Monitoring techniques selected depend on the geological setting and on the type of wells. Nevertheless, the monitoring plans do show many similarities.

In Guidance Document 2, data retention and ownership of the information from monitoring reports are considered. In Europe at present, it is up to the Member States to choose which approach to follow and to establish appropriate regulations concerning the access to and the rights to use the information. It is important to balance between proprietary rights and the transparency for public. Eminent participants (scientists, stakeholders, regulators) are of the opinion that openness and transparency should be a top priority. At least two reasons exist for such conviction: firstly the ability to develop new knowledge through circulation of information and secondly to build public confidence in CCS technology. However, how, who and to what extent to communicate the monitoring results (and other information on CCS in general) remains ambiguous.

Directives and regulations related to storage site remediation (Chapter 5)

Remediation measures are applied in case a significant irregularity in the behaviour of a storage site or a leakage of CO_2 from a storage site occurs. They can be divided into three categories, depending on the nature of the event. The first category applies to wells and includes well intervention techniques that can mostly be based on proven practice from the oil and gas industry. The second group refers to leakage through geological pathways like caprock failures or faults. In this case the remediation measures usually involve injection and pressure management modifications and/or use of low-permeability “healing” materials. The third case is leakage into overlying aquifers (including potable groundwater resources and near-surface structures) where techniques common in hydrogeology and pollution control are considered.

A special group of newly developed techniques, directed specially at remediation of CO_2 storage sites, include application of special materials (special cements, self-healing substances, etc.) or specifically tailored aquifer management techniques. These techniques are the subject of intensive on-going research and development, and further improvements in this field are expected in the near future.

Remediation measures are an integral part of regulatory regimes for CCS in all relevant countries and regions where CCS activities are on-going or planned. The CO2QUALSTORE guideline (Aarnes *et al.*, 2010) considers contingency and remediation planning an essential part of the risk and uncertainty management, providing a systematic approach to the issue. The European regulatory framework is based on the EU CCS Directive (2009) and Guidance Documents 1 and 2 (2011). The key instrument is the risk-based and site-specific corrective measures plan which has to be prepared by the storage site operator as part of storage permit application.

The international comparison shows that most of the regimes are based on similar foundations, closely linking risk assessment, monitoring and remediation measures into one mutually interconnected package. The European and U.S. legislations appear to be the most detailed and most elaborated.

Directives and regulations related to storage site closure and post closure (Chapter 6)

This chapter provides an overview on the methods and the regulatory requirements for CO_2 injection sites over the period of closure and post closure. It is structured chronologically, starting with the process of abandoning the injection wells and concludes with an overview of how the liability for the project site can be transferred to the relevant authorities.

The first part briefly discusses the different regulations concerning CO_2 site closure, which are still under development (especially the national directives). The chapter also provides information on already existing requirements for well abandonment in the hydrocarbon industry, using international conventions as well as accessible regulatory data from countries engaged in oil and gas production. The regulations for decommissioning of oil and gas production operations have already served as a general basis for developing guidelines concerning the handling of CO_2 sites because of the similarity of the subject.

Among the activities conducted during site abandonment, well abandonment is considered the most important process, as it should prevent all physical hazard induced by the well, prevent any migration of contaminants and ensure that no communication between originally separated hydrological systems is occurring. Therefore, the chapter also provides a brief overview on the potentially required technical details (plug placement) as well as overall objectives of proper well abandonment (preserve hydrogeological systems).

Following well abandonment, the post-closure phase is described, starting with a brief discussion on how to prove the safety of stored CO_2. After summarising the iterative process of characterisation of the reservoir, the general requirements for long-term storage safety, certain modelling techniques, risk management and suitable monitoring options are discussed. As all monitoring plans must be chosen according to the particular risks of the project, a variety of monitoring options also are presented.

The last step in the post-closure phase is represented by the transfer of liability. Exemplary regulations, like the EU Guidance Documents are discussed briefly.

Generally the phase of closure and post-closure is the part of the CCS life-cycle that has been practised the least, which leaves room for developments and discussion, especially concerning the final step of transferring the responsibility of the site.

Conclusions and recommendations (Chapter 7)

Based on this regulatory overview, several issues regarding CO_2 storage risk legislation could be identified. A number of these are already addressed by the instances involved. Recommendations are given here with the objective to facilitate permitting and administration, but also to create more transparency on liabilities and to facilitate the commercial introduction of CCS.

- Because regulations on storage are elaborate and newly introduced, overlaps with other national and international legislations exist that interfere and sometimes contradict them. Overlaps generally occur between specific and non-specific CCS legislation such as those for water or waste management. These overlaps need to be properly addressed, and care must be taken to ensure transparent and stable regulations for the (storage) operators. Most overlapping legislations are currently undergoing revision.
- Leakage is not uniformly defined in different regulations. This should pose no direct problems, but again different and contradicting regulations might apply to the same project. Moreover, diffuse leakage may be present but not detected with the monitoring equipment used in the monitoring time interval. Such situations are currently insufficiently addressed.
- The utilisation of CO_2 (CCUS, EOR etc.) could provide the business case for jumpstarting wide-scale deployment of CCS technology and appropriate and transparent regulations should be available. Complementary regulations between oil and gas production and CCS activity is therefore needed. In general, developing a CCS legislation can benefit from experience in the oil and gas industry and legislation.
- For all legislations the long-term liability provisions need further revision and consolidation. There are few prescriptions of the requirements during the closure and post-closure stages, as there are no projects within this timeframe yet. Better definitions of necessary tasks would lead to better understanding of expectations on the operator's part. Especially under the USEPA regulations there is no description of transfer of liability for long-term stewardship after site closure, while this aspect receives significant attention in the EU CCS directive.
- Specifically for the EU, the ETS Directive contains minimum competency requirements for the verifier of the monitoring and risk assessment reports. In the CCS Directive however, there is no mention of such requirements. It may be worth considering the introduction of standards for verification bodies regarding their knowledge, experiences, independency etc. This may result in the introduction of an accreditation procedure for verifiers under the CCS Directive at different levels (national, international).
- Uncertainties are a specific issue in geology. It should be clear how these uncertainties should be handled and the the confidence levels are required in modelling as well as the accuracy levels required in the monitoring used to verify modelling results. Uncertainty management and confidence/accuracy requirements on all storage aspects should be included and set realistically, for a given storage site setting.
- Currently, there is no obligation to keep a public register of storage sites under the US EPA regulations, nor in the IEA MFR guidelines. Although the level of disclosure that is necessary is still under discussion, such a register could increase public confidence.

This review has revealed that for countries that have a dedicated CCS regulation, although some issues still exist, most risks are covered. For countries looking to implement regulations, guidelines exist and installed legislation can serve as an example. Because CCS is a relatively new technology, experience will also guide new regulations. As investment and environmental risks are large, regulators need to be sure that risks are properly managed and operators need to be confident that liabilities are covered.

1 INTRODUCTION

CO_2 Capture and Storage (CCS) is recognised as a potentially important corner stone amongst the climate change mitigation technologies in Europe and worldwide. Although individual components of the CCS value chain are proven technologies, as a whole-chain process, CCS is a new technology which was expected to reach fast implementation and at a very large scale in the energy and other industrial sectors. The concern that a rapid implementation could result in a regulatory vacuum, lead the European Commission, the USEPA and other international organisations to proactively work on relevant legislation and directives. Legislation specifically and CO_2 geological storage was also implemented at national and regional level in several regions of the world. This legal context forms the focus of this report, but is approached from the practical point in which the storage project and the related operational and safety risks are the starting point.

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These form the main chapters of this report, and care was taken that each of them can be read largely independently from the others, allowing the reader to approach the topic from the angle that is best suited to them.

During the lifetime of a storage site, the risks associated with storing CO_2 depend on many factors, including the infrastructure used, the type of reservoir, experience gained with a specific reservoir, and also the different stages of project development. It is from the different types and levels of risk that legislation and regulations are summarised and evaluated in chapters 2 and 6 focusing on storage site operation and closure respectively.

Early detection of leakage and other irregularities requires a correctly tailored monitoring plan, although this has also many other purposes, including optimising the understanding of reservoir dynamics and, with time, reliably predicting the long-term stability of a reservoir. Therefore, monitoring is a crucial part of any storage project, and thus a point of focus for directives and regulations. The salient points with regards to monitoring and regulations are outlined in chapter 4.

In the unlikely event that leakage occurs, despite risk minimisation efforts, the CO_2 storage project enters an unexpected and undesired stage. It is a situation which is typically thoroughly dealt with in the different regulations and guidelines. In any case, a project should be well-prepared for such contingency, in order to respond properly, as is discussed in chapter 3.

If CO_2 leakage is detected, direct containment of the incident usually covers only part of the actions that need to be taken. Wherever adverse effects have occurred or can be expected, remediation actions are necessary. Compared to monitoring and leakage, the focus of relevant directives and regulations is much more on liability, rather than prescribing exact actions or obligations, as outlined in chapter 5.

The following paragraphs discuss the approach taken in this report with regards to the main aspects that are considered for CO_2 storage site operational and safety risks in each of the chapters.

Storage site

A storage site is constructed to continuously inject large amounts of CO_2 in the storage reservoir. The operational phase is preceded by several other stages, which can largely be grouped under exploration, development and testing. Such activities are only briefly discussed in this report, because from a regulatory point of view they fall under existing national laws, which regulate the general activities for the appraisal of the subsurface.

The run-up to the full-scale operational phase of a CO_2 geological storage project is essential, because it is aimed to maximise the knowledge of the reservoir and the sealing structures, sets baseline values used in the monitoring campaign, and/or tests the expected behaviour of the reservoir through injections tests. A geological reservoir, nevertheless, remains a natural system of which the details can never be fully mapped. The residual lack of knowledge is the main cause of reservoir related risks.

The engineering aspects of the site infrastructure are the second source of risk. CO_2 is transported to an injection site, where it is first handled (local transport, compression, buffer storage, temperature preconditioning, etc.) using infrastructure that is located mainly at the surface, or above the sea level for off-shore installations. This operation and its related risks are not unlike that of large industrial installations where fluids are handled at large scale. Nevertheless, even though CO_2 is a relatively harmless substance when handled is small quantities, it is worthwhile considering the risks related to a full-scale industrial project. The actual injection infrastructure is the link between the surface installation and the geological reservoir.

CO_2 is generally considered as a non-hazardous substance, however this might not be always the case, e.g. when used at high-pressure, and may be corrosive to some materials. Minor additional substances in the CO_2 stream may also introduce an additional concern. Also, external risk factors, such as potential accidents due to damage to pipelines, need to be taken into account.

There is a large amount of relevant guidelines and regulations specifically designed to properly regulate the handling of CO_2 during the operation of CO_2 geological storage projects, both on- and off-shore. In addition to these ad-hoc regulations, there exists a significant amount of indirect regulations that have to be taken into account in storage projects. Some of those more general conventions even contain clauses that may be incompatible with some CCS projects, and could therefore be fundamental obstacles.

Leakage

Identification and regulation of risks and risk-related activities will minimise, but not absolutely prevent the leakage of CO_2 from a reservoir. Therefore, a second set of regulations seems necessary in order to ensure that proper actions are taken in case of leakage events.

Leakage-specific regulation indeed includes, but is usually not restricted to designing an action plan in case of leakage. In addition to this, the regulation refers for the important apects of risk evaluation and gathering of appropriate monitoring data. This is considered both logical and useful, since the identification of risks allows to anticipate the different potential scenarios under which CO_2 can leak from a specific reservoir.

Similarly, monitoring data is of essential importance, because the follow-up of the evolution of a storage reservoir provides essential insights as to whether a reservoir behaves as expected, which potential leakage scenarios become more or less likely, and what potential amounts of CO_2 can leak from specific parts of the reservoir.

However, the final target of the majority of these regulations is indeed to maximally prevent adverse effects in case of leakage. This usually requires that a fully prepared action plan is ready for deployment. Especially in the European context where the ETS forms an important part of the financial balance sheet of a storage project, regulations also need to be in place to compensate for the loss of CO_2 from a storage reservoir. In this, but also in a more general context of proper supervision, the reporting obligation to the national competent authority is strictly embedded in the European legislation and guidelines.

In order to mitigate the adverse effects of potential leakage, the effects of CO_2 in the environment into which it has leaked need to be properly understood. This again is a vast discipline in its own right, and is relatively well studied. One of the typical examples discussed is the leakage of either CO_2 or displaced brine into an aquifer that is exploited for drinking water. Although the most direct effects seem to relate to pH changes that do not necessarily negatively affect the quality of the drinking water, field experiments have demonstrated that it are mainly the secondary effects (e.g. dissolution of minerals) that result in potentially hazardous chemical changes.

In case leakage occurs through geological boundaries, this leakage is potentially a spatially diffuse process. This means that leakage mitigation actions will usually consist of controlling the stored CO_2, rather than enhance or repair the impermeable barriers. Such actions often involve reservoir engineering schemes such as the depressurisation of the reservoir, or the injection of water to steer the CO_2 plume away from a spill point.

Monitoring

Throughout the lifetime of a reservoir, and also before CO_2 injection is started, monitoring of the reservoir properties and the injected CO_2 is a crucial element for the successful completion of a storage project. At the same time, it adds significantly to the operational costs, and therefore proper regulations are useful as additional motivation for the storage operator.

Since many monitoring techniques are designed to detect relative changes, e.g. regarding densities in 3D seismic profiles, groundwater composition, or increase of CO_2 in soil gas, it is important to establish a proper baseline. Such a baseline is often the definition of the natural background values, which may by themselves be variable through time. This should be taken into account to avoid later disputes (e.g. claims regarding alleged leakage of CO_2).

A crucial aspect of monitoring that is particularly emphasised in most regulatory documents, is that active monitoring will allow to verify that the CO_2 plume is migrating as expected. Where deviations are observed, the reservoir model is to be adjusted accordingly. As such, monitoring will lead to an increasingly better understanding of the reservoir during operation, and improve the accuracy of the long and short term predictions of the reservoir in response to injection activities. This aspect has direct consequences to the appreciation of the different risks related to the geological storage of CO_2.

As a final major element, monitoring of the CO_2 plume should be performed to maximise the early detection of CO_2 leakage. Guidelines have been set up to provide an evaluation framework for the techniques that can be used. In conjunction with understanding of migration and potential leakage pathways, it is possible to decide which techniques can or should be deployed.

Due to the intrinsic variability of geological reservoirs and storage scenarios, it is difficult to turn such guidelines into absolute obligations. The approach is, therefore rather, that the proposed site operator designs a monitoring plan, in line with the objectives of the guidelines, which is then to be evaluated by an independent governmental body. The guidelines provide a reference framework for both the design and the evaluation (followed by a motivated approval or rejection) of a monitoring plan. A monitoring plan is not a final document, but will frequently be updated to reflect the increasing knowledge of the reservoir. This report illustrates how such a process works in practice by discussing the few early projects that have partly or fully undergone through the process of setting up and submitting a monitoring plan.

Remediation

The chapter on how remediation is regulated focusses on which actions are required in case significant irregularities occur in a CO_2 geological storage project. A significant irregularity covers situations where there is direct (threat of) economic or environmental damage or endangerment of a human population.

It is useful to distinguish different categories of such situations, simply because they often relate to which remediation actions can be considered. Although, as is shown in the chapter on risks related to site operation, irregularities may also relate to the surface installations, the focus of this chapter is on subsurface problems in or around a reservoir. In that context, the cause of the problem is either natural (geological) or anthropogenic pathway.

A typical case of leakage along an anthropogenic pathway is leakage along an abandoned well. In such case, remediation is taken in two steps. The first is the identification (localisation) and resealing (potentially including a work-over) of the well. The second involves the remediation of the damage done. Again taking a typical situation, leakage may have resulted in the contamination of an aquifer. In such cases, remediation may involve pump-and-treat to actively remove primary and secondary contaminants, and possibly also the restoration of the pH condition in the aquifer.

When an irregularity has a geological origin, the identification step is likely more complex because the cause of the irregularity is generally less localised. In such instances, reservoir engineering solutions can still offer a way out. The report discusses a variety of situations that may occur, and remediation actions that can be considered, before discussing the relevant regulatory regimes and guidelines.

Especially in the European context, the implementation of remediation actions is explicitly embedded in the legislation. The operator needs to report any irregularity immediately, resulting in a direct involvement and supervision of the situation by the national competent authority, who has large freedom in ordering remediation actions as well as including those not foreseen in a remediation plan. In case the operator fails to comply, they can ultimately be relieved of site operation duties.

Closure and post closure

An essential step in any project that envisages permanent CO_2 storage is the post-operational phase of the project. As a general rule, the risk on leakage decreases over time with different geological processes that slowly but steadily increase the stability of the stored CO_2.

The level of risk is, however, determined by the abandonment procedure, e.g. the sealing or otherwise final closure of the wells that were used during the operational phase. Actually, well abandonment is considered as one of the most crucial points of the site closure process. The process is not unlike standard well-abandonment of oil and gas fields, but specific precautions should be considered for CO_2 storage sites.

Until the injected CO_2 is fully stabilised, or at least until its behaviour can be fully predicted, monitoring will remain necessary, be it according to a scheme modified to a situation where there is no longer active injection.

In Europe, a system in which the responsibility for a reservoir, once the operator has convincingly been able to show that it will evolve to stability, is handed over to the state authorities. This has the advantage that long-term responsibility is guaranteed. Naturally, the hand-over of such previous injection sites is a point of attention for the regulator.

In general, proving the safety of a post-closure project involves a specific risk assessment in relation to modelling, an evaluation of the historical monitoring record, the demonstration that mainly wells are adequately abandoned, and of course the absence of environmental problems. In normal situations, transfer of liability is not foreseen to be problematic. Naturally, no industrial scale project has reached the point where site closure is practically being considered or prepared.

2 CO_2 STORAGE SITE OPERATION RISKS AND REGULATIONS

This chapter identifies the risks related to the injection phase during CO_2 geological storage and summarises the national, European and international legislation of CO_2 geological storage and CCS-related legislations. The materials presented provide an overview of the risks arising during the CO_2 storage operation phase. Risks are described with regards to their spatial extent and significance: local environmental risks, general operational risk, risks related to CO_2 stream composition, pressure and temperature.

The directives and regulations relating to CO_2 storage site operation are discussed with a special focus on dedicated CCS legislations at international, European and national levels where available. Besides the CCS specific regulations, the EU Emission Trading Directive, the International Climate Change Legislation and Clean Development Mechanisms and their relations to CO_2 storage site operation phase is considered. Next, the directives and regulations relating to offshore and onshore CO_2 storage site operation are presented, followed by brief conclusions.

During storage operation, the CO_2 is transported from the source location(s) and injected into the storage reservoir according to the volumes and rates specified in the site development plan (Groenenberg *et al.*, 2009). The site operation phase (Fig. 2-1) is one of the most important periods from a risk management perspective, because large scale commercial CO_2 injection into the storage complex is initiated and conducted and the risk of irregularities and potential leakage as a result of the injection project is highest. During the site operation phase, the migration and movement of CO_2 may follow different pathways as the plume develops and expands, and pressures start to increase, also affecting risk evolution (ICF, 2011).

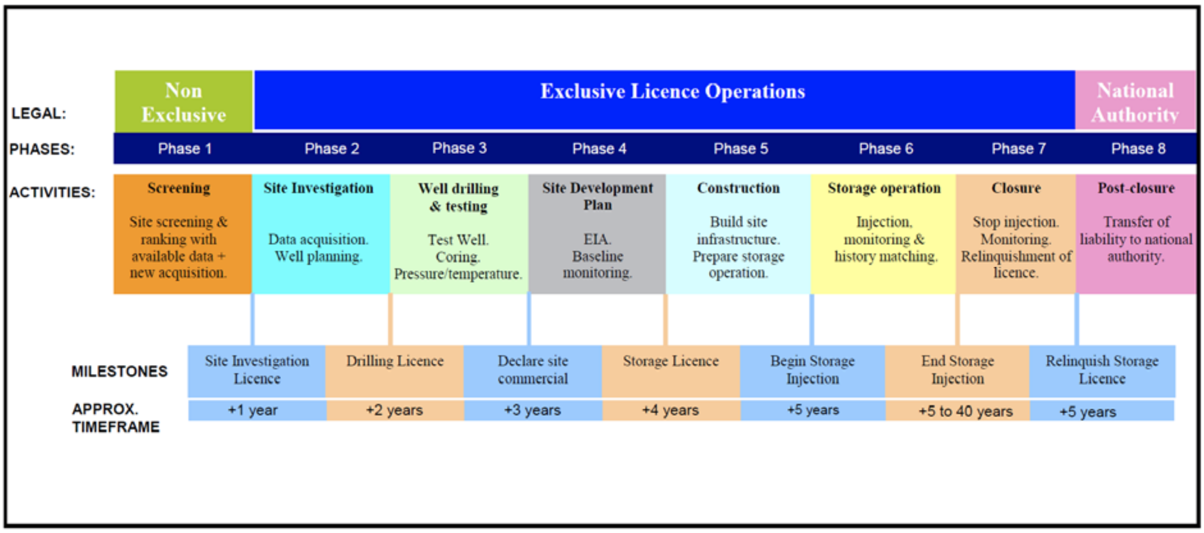

Fig. 2-1: Phases of CO_2 storage site operation (Groenenberg *et al*., 2009).

The storage operation activity follows several licencing procedures, i.e., site investigation, drilling and storage licencing procedures, which infer the use of a 3D geological model, a monitoring plan and that detailed risk assessment has been carried out. The key aspects of the operation phase are the need to evaluate the degree to which the site is performing as expected according to predictive models that have been used to carry out performance assessment and evaluate the evolving containment risks through on-going risk assessments. Performance and risk assessments should be carried out at intervals determined in discussion with the regulator (at least once a year according to the EU CCS Directive (2009/31/EC).

With on-going monitoring, there will be a continuous flow of new information and data about the project and its performance. The monitoring plan and activity are essential parts of the risk management approach. The results from injection and monitoring should be used by the operator to verify, test and iterate the risk assessment, validate models and performance predictions iteratively. The results may require that operational parameters and limits stated in the original site development plan be adjusted to reflect updated understanding of the storage performance (Fig. 2-2). The results must also be reported to the competent authority in line with the CCS Directive. The CCS directive also requires a range of necessary actions and safeguards to be in place because of the risk arising from the injection of large volumes of CO_2.

Fig. 2-2: Risk Management based approach to storage project (EC, 2011a).

2.1 Risks arising during CO_2 storage operation

The following sections focus on types of risks (physical, chemical and biological conditions and accidents) arising during the CO_2 storage operation phase and discuss how directives and regulatory regimes cover these risks.

2.1.1 Local environmental risks related to CO_2 storage operation

The assessment of local environmental risks, such as: permeable zones in the storage formation seal; leakage through undetected faults; leakage via wells; regional scale over-pressurisation; exceeding reservoir spill point and earthquake induced fractures, are necessary considerations when preparing a monitoring plan, which a major input for a storage permit application (DNV, 2009). During storage operation potential environmental risks are carefully monitored and the interpreted monitoring data is used to determine site performance and compare it to the predicted behaviour.

If the comparison/deviation is within a predefined range, the results are used to update the geological model as well as the monitoring plan (every five years as a minimum requirement). The competent authority reviews the storage permit using the monitoring and performance verification results. However, if any serious deviation from predicted behaviour is detected, in other words “significant irregularity”, this must be reported to the competent authority. Preventive and corrective measures, according to the plans in the storage permit as well as on-going consultation with the competent authority, must take immediate action. Monitoring and corrective measures are closely interlinked and the plans and activities should be developed by the operator in a holistic manner along with the risk assessment. The competent authority should seek to ensure close integration between these measures. The deployment of corrective measures is required in the event of leakages or significant irregularities, and these would usually be detected by monitoring results or the interpretation of monitoring data or inspections. In addition, monitoring is used to assess the effectiveness of corrective measures, and additional monitoring activities may be required in event of any leakage or significant irregularities. According to the EU CCS Directive (2009), the occurrence of significant irregularities may result in the withdrawal of the storage permit.

2.1.2 General operational risks related to CO_2 injection

The main concerns regarding CO_2 storage operations is connected to possible failure of pipelines, wells or other components that could lead to CO_2 releases causing health and safety concerns for humans and/or the environment. CO_2 is a substance occurring naturally in blood gases of the human body and is not classified as a hazardous chemical, but if inhaled in sufficiently high concentrations it can have toxicological effects. The dangers of breathing in elevated concentrations of CO_2 are well known to people such as divers and anaesthetists. Outside these groups of specialists, knowledge about the impact of breathing elevated concentrations of CO_2 is generally low. Moderately elevated levels of CO_2 (2-6 %) induce adverse effects on humans such as headache, sweating, dizziness and difficulty in breathing. Very high levels of CO_2 may cause confusion, unconsciousness, coma and death (asphyxiation by displacing oxygen in the air). A large leak of CO_2 from a CCS operation has therefore the potential to be life threatening to people who might be caught within the subsequent CO_2 cloud. CO_2 cannot be seen or smelled, it provides no evidence of its presence that can be recognised by the senses.

The main technical considerations relating to risk of CO_2 storage operations are the gas stream composition, temperature and pressure conditions. The effect of a potential CO_2 release would, however, also depend a lot on several external factors. Such factors need to be taken into account during risk assessment and include the following: environment (subsea, subsoil, offshore, onshore, platform, vessel, confined space etc.), topography, wind and temperature conditions. Since CO_2 is heavier than air, it remains close to the surface of the space in a deep or shallow pool, therefore, topography considerations need to be taken into account when planning CO_2 injection infrastructures, i.e. pipeline routing.

Liquid CO_2 is a powerful solvent that can have unwanted effects on some lubricants and is also highly invasive and capable of penetrating materials and causing damage. Seal elastomers are known to be vulnerable to explosive decompression damage, particularly when exposed to supercritical CO_2. This means that careful selection of materials is very important for seals, flexible hoses, instruments, wire and cable insulators, controls and other safety-critical components (DNV, 2013).

Since CCS is a reasonably new technology, the industry and operational standards are still not generally accepted. Therefore, there is still a possibility that unknown effects and hazards could develop during the operational phase. Increase of experience and the stringent use of existing hazard management processes will reduce the likelihood of this to an acceptable level (DNV, 2013).

Besides the main technical considerations relating to risk of CO_2 storage operations, the borehole operation itself may pose risk to the groundwater zone and proper well surface casing and cementing at appropriate depths is required to ensure isolation of protected groundwater sources and control of the well under maximum formation and operating pressures.

All site activities need be performed in a manner that avoids endangering protected groundwater sources. Surface pipe should be set to a depth sufficient to ensure control of the well under maximum formation pressures and operating pressures prior to the next casing interval. Casing the well begins with the large-diameter conductor pipe being driven or augured into the ground through the surface rubble or loam to hard pan, usually to a depth of 8 to 30 m. The conductor pipe prevents caving and washout at the rig base and provides containment of the cement for the surface casing at ground level. Once in place, the conductor casing is grouted with cement to maintain integrity around the casing and to prevent washouts.

The well should be drilled out through the conductor to below protected groundwater sources and the surface casing should be run and cemented back to the surface to protect any groundwater sources encountered. The well should be drilled to total depth and cased with the appropriate grade, weight, and size of casing to handle the operating parameters expected in the well and should be cemented back to the surface. At a minimum, the design of the casing should account for the internal yield strength of the pipe, casing collapse pressure, the pipe body yield, the required internal diameter of the pipe, and the corrosion resistance of the metallurgy.

2.1.3 Operational risks related to CO_2 stream composition

It is required that the CO_2 stream shall consist overwhelmingly of CO_2. This is to ensure that the CO_2 stream does not negatively affect the integrity of the storage site or transport facilities and to prevent any significant risk to the environment or human health. The exact composition of the stream is highly dependent of the source and capture processes used. The main issues associated with CO_2 stream composition are listed in Tab. 2-1.

Tab. 2-1: Main issues associated with selected incidental substances of a CO_2 stream (modified after DNV, 2010).

Component	Health & Safety	Pipeline capacity	Water solubility	Hydrate formations	Materials	Fatigue	Fractures	Corrosion	Operations	Comment
CO_2	X	X	X	X	X	X	X	X	X	Non-flammable, colourless, no odour; low toxicity,heavier than air in the gaseous state
H_2O				X	X	X	X	X	X	Non-toxic; condensable; forms acids with CO_2, NOx and SOx, which have a corrosive impact on transport infrastructure
N_2		X	X							Non-toxic; stable
O_2		X	X					X		Non-toxic
H_2S	X	X			X	X	X	X		Flammable, strong odour, extremely toxic at low concentrations
H_2		X	X				X			Flammable, non-condensable at pipeline operating condition; potential impact on transport infrastructure through embrittlement
SO_2	X		X					X		Non-flammable, strong odour, toxic; forms sulphuric acid with water
NO_2	X		X					X		Non-flammable, toxic; forms nitric acid with water
CO	X		X							Flammable, toxic
CH_4		X	X						X	Odourless, flammable
Amines	X									Potential occupational hazard, with corrosive impact
Glycol	X							X		Potential occupational hazard

The three main transportation risks associated with impurities in the CO_2 stream are: corrosion, gas hydrate formation, and pipeline flow characteristics. While some minor substances can be safely transported in pipelines, they might have a negative effect on their integrity.

Corrosion of pipelines may occur if there is too much water in the CO_2 stream, since it may form acids that corrode the pipelines. The CO_2 stream composition could influence the choice of pipeline materials and thickness such as to ensure that safety requirements are met. Consideration of water concentration limits for pipeline corrosion is likely sufficient to address corrosion in other infrastructure components (pumps, valves, injection tubing). CO_2 leakage through existing cracks could also lead to the acidification of water outside the pipe causing external corrosion. In addition to corrosion, water in a CO_2 stream can also increase the risk for hydrate formation. Hydrates form at temperatures higher than the freezing point of water and its solid like property makes it a danger for pipelines (Carroll, 2003). Hydrates can form in liquids and gases, favourably in low temperatures and high pressure and are therefore mostly a concern for offshore operations. The main strategy for preventing hydrate formation is sufficient dewatering of the CO_2 stream (DYNAMIS, 2007).

Oxygen in a CO_2 stream can also have corrosive effects in pipelines. In Enchanced Oil Recovery (EOR) another key risk related to oxygen is that it reacts with oil and can cause overheating of injection equipment (IEA GHG, 2004; DYNAMIS, 2007). The DYNAMIS project report (2007) notes that it can be useful to place oxygen sensors in the injection and production wells for EOR to ensure that these wells do not overheat. However, an early report in 1985 indicated that injection of small amounts of O_2 in EOR applications should not have significant impacts, and the main issue was corrosion (Taber, 1985). Taber (1985) also suggests that flue gas injection with 1-2% oxygen and air injection for in-situ combustion for EOR takes place without serious corrosion problem, as long as there is sufficient dewatering. However, further research is necessary to assess the impact of O_2 in CO_2 streams for storage.

Long distance transportation of CO_2 is most efficient and economical in the liquid or supercritical states (DNV, 2010). Getting to the supercritical fluid flow is made more difficult by the presence of non-condensable gases such as hydrogen (H_2), argon (Ar), nitrogen (N_2), oxygen (O_2) and methane (CH_4), as higher pressure is needed to convert CO_2 into the supercritical fluid (DYNAMIS, 2007). Models used need to predict the phase envelopes for the range of mixtures likely to be present. The cost of CO_2 purification is important for the total cost of CCS as it affects many other parts such as transportation and storage.

Acid gases can be transported safely in pipelines as long as the stream is sufficiently dehydrated, but interactions will occur with formation water in the storage site. Of particular importance are the potential deterioration of wellbore cement and other geochemical changes from acid interactions (chemical reactions and mineral dissolution and precipitation, along with related permeability enhancements and clogging effects) with the fluids and rocks in the storage formation and heavy metal contamination of deep saline aquifers.

Some of the incidental substances found in the CO_2 stream are toxic, such as CO, NO_2, SO_2 and H_2S, and may further influence the potential impacts of a pipeline leak or rupture (IPCC, 2005). Because low levels of H_2S are tolerated by the human body quite well, H_2S would mainly be a safety concern for the general public living along the pipeline route or workers who would be operating and maintaining the pipeline and pumping stations, where the concentrations of H_2S from potential leakages could be higher.

When SO_2 is inhaled it can cause immediate irritation in the throat and a sensation of tightness and difficulty in breathing. People with asthma are more sensitive to these health effects and could react to concentrations of SO_2 below 1ppm (DYNAMIS, 2007). NO_2 is a very toxic gas and exposure at low levels may result in unconsciousness or death. The SOx and NOx produced from air-combustion would be removed in post-combustion capture processes in order to achieve the longevity requirements of acid gas removal and amine solvents (Tzimas *et al*., 2007). If SOx and NOx are not removed from the CO_2 streams from oxyfuel combustion, oxy-fuel combustion will be the source of most of the SOx and NOx.

Amines used in post-combustion CO_2 capture can be degraded to different harmful substances such as aldehydes, amides, nitrosamines, and nitramines, some of which have been found to be carcinogenic (Låg *et al*., 2009). Release of these substances to the air, drinking water or the aquatic ecosystems may need to be limited and several studies are underway to evaluate such effects (da Silva *et al.*, 2013).

Small amounts of tracer substances can be added to the CO_2 stream for monitoring and verifying the location and migration of the CO_2 plume. Although these substances are no serious health risk in small amounts, the health impacts on operators should be considered (EPA, 2010).

2.1.4 Risks related to CO_2 stream pressure and temperature

CO_2 phase changes may occur when it is depressurised, depending on the initial and final pressure and temperature conditions. The depressurisation of CO_2 by design or by accident can result in the sublimation temperature of solid CO_2. In addition, significant quantities of solid CO_2 can be formed within systems and/or within any release which in addition to its low temperature could cause blockages, and subsequent hazard. Having an adequate understanding of the thermodynamics of the CO_2 stream, including the effects of the impurities, is essential within the design and operation of CO_2 stream handling systems. Low temperatures could lead to the embrittlement of materials causing fractures and cracks (DNV, 2013).

CO_2 density is also sensitive to temperature changes especially close to critical point conditions (i.e., 31 °C and 74 bars, see Fig. 2-3). This can lead directly to system over pressurisation with a relatively small change in CO_2 temperature. Appropriate system pressure relief should avoid this leading to a hazardous event (DNV, 2013).

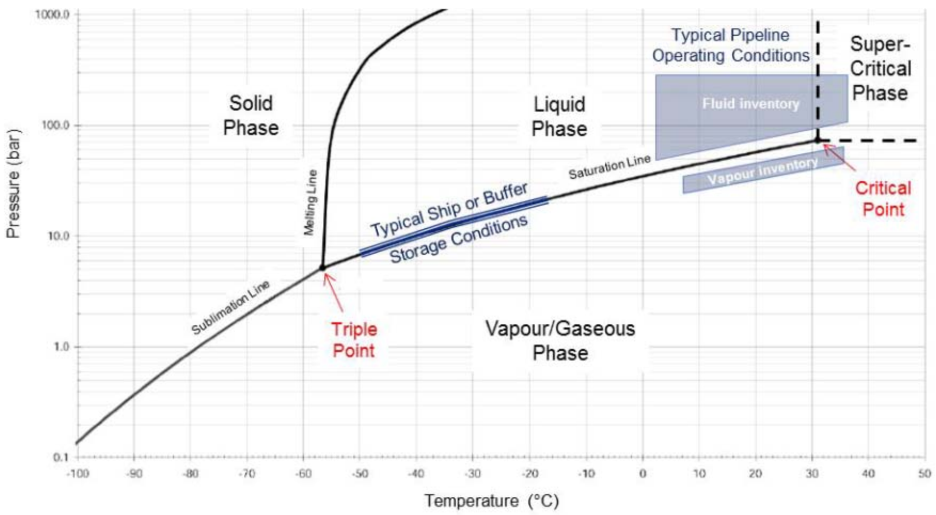

Fig. 2-3: CO_2 phase diagram with typical transportation conditions (DNV, 2013).

A rupture of e.g a vessel containing large amounts of liquid CO_2 could lead to rapid pressure reduction which under certain conditions could escalate to create a Boiling Liquid Expanding Vapour Explosion (BLEVE). The probability of this occurring is believed to be extremely low but CO_2 system designers should be aware of the potential (DNV, 2013).

Induced seismic activity has mainly been recognized along previously faulted rocks at waste disposal sites, oil fields, and other sites. Supercritical CO_2 liquid is less dense than water and may cause density-driven stress conditions at depth or interact with formation water and rocks, causing a reduction in permeability and pressure build-up leading to seismic activity. Seismic events are unlikely to occur due to injection in porous rocks unless very high injection pressures cause hydraulic fracturing. Thorough characterisation, testing, and monitoring of stress conditions at depth will prevent the risk of unexpected seismic events (Sminchak and Gupta, 2002).

Possible health and safety risks related to CO_2 stream pressure and temperature include inhalation of, or exposure to, very cold air mixture, contact with solid CO_2 or cooled surfaces, rapid expansions, explosions and projectiles.

2.2 Directives and regulations relating to CO_2 storage site operation

The Global CCS Institute hosts a Carbon Capture Legal programme (CCLP), which was originally started in 2007 by University College London (UCL). This open access database is used extensively in this section as a reference source (http://www.globalccsinstitute.com/networks/cclp).

2.2.1 Dedicated CCS legislation

2.2.1.1 EU Directive 2009/31/EC on the geological storage of carbon dioxide

The Directive applies to geological storage of CO_2 within the territory of the Member States, their exclusive economic zones and on their continental shelves, thus envisaging storage both onshore and offshore.

During the operation phase, the operator is obliged to monitor and report on activities and if required, allow inspections. Concerning the storage permit, the EU CCS Directive (2009) guides that if there are any planned changes in the storage site operation, the competent authority shall be informed. The competent authority reviews and, when necessary, updates or withdraws the storage permit (Article 11, Directive). The Directive Article 12 defines the CO_2 stream acceptance criteria and procedure, and the Article 12 point 1 states that:

'A CO_2 stream shall consist overwhelmingly of carbon dioxide. To this end, no waste or other matter may be added for the purpose of disposing of that waste or other matter. However, a CO_2 stream may contain incidental associated substances from the source, capture or injection process and trace substances added to assist in monitoring and verifying CO_2 migration. Concentrations of all incidental and added substances shall be below levels that would:

a) adversely affect the integrity of the storage site or the relevant transport infrastructure;

b) pose a significant risk to the environment or human health; or

c) breach the requirements of applicable Community legislation.'

The Guidance Document 2 (EC, 2011b) helps in defining the criteria for CO_2 stream identified in the Article 12. The article indicates, that Member States shall ensure that the operator accepts and injects only CO_2 streams, only if an analysis of the composition of the streams and risk assessment have been carried out. The operator has to keep a register of the quantities and properties of the CO_2 streams delivered and injected, including the composition of those streams.

Reporting should be prepared at the least annually and it should cover the topics identified in the EU CCS Directive; namely, should provide quantities and properties of the CO_2 streams delivered and injected, all monitoring results and description of the monitoring methods used, proof of putting in place and maintaining the financial security and any other information that the competent authority considers relevant for the purposes of assessing compliance with the storage permit conditions and improving the knowledge of CO_2 behaviour in the storage site.

According to the CCS Directive, the competent authorities must design a system of routine and non-routine inspections for all storage complexes as specified in the scope of the Directive (Art. 15). Routine inspections must be carried out at least annually. For non-routine inspections, Article 15 provides a list of events and situations which trigger a duty on the competent authority to carry out one. These include, for example, leakages and complaints related to the environment or human health.

European Commission Guidance Documents

The European Commission has published a set of four Guidance Documents to assist stakeholders in the implementation of the CCS Directive in order to promote a consistent approach throughout the European Union. These documents cover: (1) the CO_2 storage life cycle risk management framework (EC, 2011a); (2) characterisation of the storage complex, CO_2 stream composition, monitoring and corrective measures (EC, 2011b); (3) criteria for transfer of responsibility to the competent authority (EC, 2011c); and (4) financial security and financial mechanisms (EC, 2011d).

The Guidance Document 1 “CO_2 storage life cycle risk management framework” (EC, 2011a) deals with risk management throughout the storage operation. In this document, the operation phase is considered as one of the most important periods from the risk management perspective, because during this phase large scale commercial CO_2 injection into the storage complex is initiated. This is the first phase in the storage site life cycle when risk of potential irregularities and leakage as a result of the injection project exists.

The Guidance Document 2 “Characterisation of the Storage Complex, CO_2 Stream Composition, Monitoring and Corrective Measures” (EC, 2011b) provides detailed information relevant to the CCS Directive. Concerning the CO_2 stream composition, the focus in the Guidance Document is on the other substances in the CO_2 stream. The document provides definitions related to Article 3 on incidental substances and added or tracer substances and proposes an approach to determine an acceptable CO_2 stream composition (Fig. 2-3).

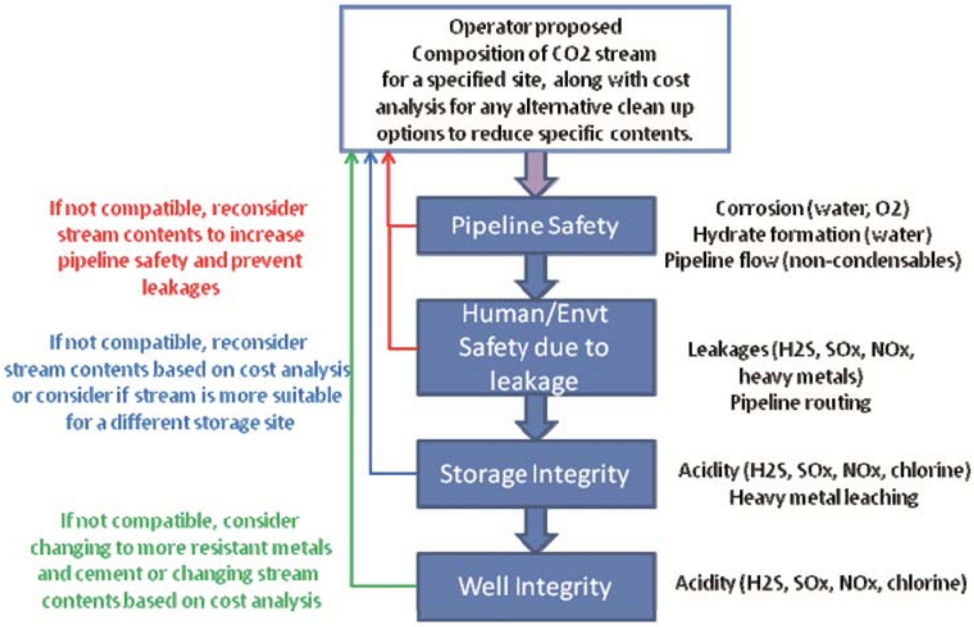

Fig. 2-4: Proposed approach to determine acceptable CO_2 stream composition (EC, 2011b).

2.2.1.2 *National legislations*

EU member states and European Economic Area/Associated states

The EU CCS Directive (2009/31/EC) established a legal framework for the environmentally safe geological storage of CO_2 which required that member states should bring into force the laws, regulations and administrative provisions necessary to comply with this Directive by June 25th 2011, as well as ensure that any storage sites are operated in accordance with this Directive by June 25th 2012. By January 2013, the CCS Directive has been fully transposed into national law to the satisfaction of the EC in 20 out of 28 EU member states and will shortly be transposed in six other EU countries (Austria, Cyprus, Hungary, Ireland, Sweden and Slovenia) (Shogenova *et al*., 2013). The transposed the CCS directive is currently undergoing evaluation in Poland (the directive was transposed at national level in November 2013) and in Croatia, which entered the EU on 7th July 2013 and simultaneously transposed the directive (Shogenova *et al*., 2013).

In Norway, a European Economic Area state, the CCS Directive entered into force in June 2013. Although until now CCS activities have been regulated under existing acts and regulations, two new sets of regulations on transportation and storage of CO_2 on the continental shelf have been under preparation in 2013. Turkey, an associated EU Member State, has to transpose the Directive at a later date, starting with the preparation process to join ETS (European Emission Trading System) in 2014 (Shogenova *et al*., 2013).

Nevertheless, several governments have applied at least temporary restrictions on CO_2 storage. In Denmark, regulations have prohibited storage until 2020, although offshore CO_2-Enhanced Oil Recovery operations may be permitted. In Germany, only limited CO_2 storage will be permitted until 2018 (up to 4 Mt CO_2 annually). A temporarily ban applies in Austria (until 2018), the Czech Republic (until 2020). In Bulgaria, the size of exploration areas for CO_2 storage sites is limited. CO_2 storage is prohibited in Sweden (until January 2013). The same applies in Poland (until 2024) except for demonstration projects. Estonia, Latvia, Finland, Ireland, Luxembourg, Slovenia and two regions in Belgium (Brussels Capital Region and off-shore Belgium) have prohibited CO_2 storage except for research and development. Additionally, CO_2 storage is not permitted in seismic areas in Italy, and in Greece in areas where the storage complex extends beyond Greek territory (Shogenova *et al*., 2013).

Australia

In Australia, several federal and state level regulators both offshore and onshore are in act. These are further described under the regulations for offshore and onshore CO_2 storage sections.

Canada

In Alberta, two sets of regulations are in act. The first is Carbon Capture and Storage Statutes Amendments Act 2010 (BILL 24) and the second is Carbon Sequestration Tenure Regulation (AR 68/2011).

The Carbon Capture and Storage Statuses Amendments Act 2010 amend a number of other statutes (the Energy Resources Conservation Act; the Mines and Minerals Act; the Oil and Gas Conservation Act; and the Surface Rights Act) to clarify the regulatory structure for CCS in Alberta. The Act vests in the Alberta Government the ownership of pore space and provides it with the authority to grant licences and leases for the injection of CO_2. The amendments to the Mines and Minerals Act define the pore space and one part defines the sequestration of captured carbon dioxide. The definitions are given for the right to drill evaluation wells, rights to inject captured carbon dioxide for sequestration, prohibition, restriction on transfer of agreement, duties on cessation of injection and for closure certificate. In rights to inject captured carbon dioxide for sequestration, Section 116(3), it is stated that monitoring, measurement and verification plans have to be submitted and complied, reporting has to be done with respect to the lessee’s compliance and that the work requirements with respect to the location of the agreement need to be fulfilled (BILL 24, 2010).

The Carbon Sequestration Tenure Regulation (AR 68/2011) establishes the process for obtaining pore space tenure rights for carrying out CO_2 geological storage. The regulation is made under the authority of the Mines and Minerals Act (ss. 5 and 124), which was amended by the Carbon Capture and Storage Statutes Amendment Act in 2010 to enable CO_2 storage. The regulation sets out the terms for an evaluation permit, which grants the permit holder the right to carry out activities to evaluate the suitability of a subsurface reservoir for CO_2 storage. The regulation also establishes details of a carbon sequestration lease, which grants the lessee the right to drill wells, conduct evaluation and testing, and inject captured CO_2 into the geologic reservoirs within the lease area (AR 68/2011).

USA federal legislation

In Federal Requirements under the Underground Injection Control (UIC) Program for Carbon Dioxide (CO_2) Geologic Sequestration (GS) Wells (2008) EPA is proposing Federal requirements under the Safe Drinking Water Act (SDWA) for underground injection of carbon dioxide for the purpose of geologic sequestration. It proposes four different schemes for regulations, and from these EPA is proposing Regulatory Alternative 3, the Tailored Requirements Approach. The technical requirements of this alternative build upon the existing UIC regulatory framework for deep wells and are appropriately tailored to address the unique nature of full-scale CO_2 GS. EPA's operating requirements for deep injection wells provide multiple safeguards to ensure that injected fluids do not escape and are confined within the injection zone and that the integrity of the confining zone is not compromised by non-sealing artificial penetrations or geologic features. In the proposal, some well operating requirements are consistent with existing UIC well types and some requirements are tailored specifically for CO_2 injection (USEPA 2008).

Interstate Oil and Gas Compact Commission, Storage of Carbon Dioxide in geologic structures, A Legal and Regulatory Guide for States (IOGCC Task Force on Carbon Capture and Geologic Storage, 2007) purpose is to provide to a state or province contemplating adoption of a legal and regulatory framework for the storage of carbon dioxide (CO_2) in geologic media the resources needed to draft a framework that meets the unique requirements of that particular state or province. Section 7.0 details the operational standards and requirements with which CO_2 storage project operators must comply in implementing the approved safety, corrosion monitoring and prevention, leak detection, and reporting programs approved in the permit issued by SRA. Section 8.0 of the regulations specifies the reporting requirements that serve to demonstrate and document that CO_2 storage projects and associated wells are operated in accordance with all approved operating parameters and procedures, including limitations on injection pressures and temperatures; prescribed chemical constituents and composition of the CO_2; status and projections of storage response and capacity; monitoring of corrosion and corrosion prevention plans and/or all other operating parameters and procedures as specified in the CO_2 project permit issued by SRA. Quarterly and annual reports are required.

USA state legislation

There are several CCS related acts currently in force in numerous states. Listed below are the acts that relate to CO_2 storage site operation.

Montana

SB 498 (2009) is an Act regulating Carbon Capture Sequestration, which establishes a permitting system for CO_2 storage. It establishes requirements for site characterisation, injection conditions and reporting obligations.

Texas

SB 1387 (2009) is an Act relating to the implementation of projects involving the capture, injection, sequestration, or geologic storage of carbon dioxide. It establishes permit conditions, requirements for conversion of use and ownership of stored CO_2.

HB 1796 (2009) is relating to the development of carbon dioxide capture and sequestration in this state. This Bill establishes a scheme to regulate the location, construction, maintenance and monitoring of an offshore geological reservoir for the purpose of CCS operations, including provisions on fees, ownership, and liability.

Utah

SB 202 Substitute (2008) is an Energy Resource and Carbon Emission Reduction Initiative. This Bill requires specified state agencies to draft recommendations for CCS legislation, including site characterisation, permitting procedures, technical standards and monitoring requirements.

Washington

Washington WAC 173-218-115 (2008) defines Specific requirements for Class V wells used to inject carbon dioxide for permanent geologic sequestration. It revises Washington UIC (Underground Injection Control) rules for geological storage.

Washington WAC 173-407-110 (2008) sets performance standard for geological storage.

Wyoming

(HB 90) HEA25 (2008) is an Act relating to carbon sequestration Bill and it provides the Wyoming Department of Environmental Quality with the authority to regulate the long-term storage of CO_2.

(HB 58) HEA20 (2009) is an Act relating to carbon sequestration. This Act provides a rebuttable presumption that the injection operator is the owner of any materials injected into a geological sequestration site, such ownership including incidental "rights, benefits, burdens and liabilities". The Act also clarifies that no owner of the pore space is to be liable for the effects of injection simply by virtue of their interest or having given consent.

2.2.2 EU Emission Trading Directive

The EU Emission Trading Directive (Directive 2003/87/EC) was adopted in 2003 (Commission Decision 2007/589/EC), and the Revised EU Emission Trading Directive (Directive 2009/29/EC, EU CCS Directive, 2009b) was adopted in 2009. Under the 2009 ETS Directive, a new paragraph 3a is inserted into Article 12 of the original Directive. This removes the obligation to surrender allowances where emissions have been verified as captured and transported for the purpose of permanent storage, in accordance with the new CCS Directive (2009/31/EC). In addition, no free allocation is to be given to operators in the power sector undertaking the capture and storage of CO_2. On 8 June 2010, the Commission adopted a decision establishing a set of guidelines for monitoring and reporting greenhouse gas emissions from the capture, transport and geological storage of carbon dioxide.

2.2.3 International Climate Change Legislation and Clean Development Mechanism

The Kyoto Protocol, which was agreed in 1997, provides Contracting Parties with legally binding obligations and targets for the reduction of their greenhouse gas emissions. It shares the Convention's aims, principles and institutions, but requires developed countries (those listed in Annex I) to reduce their emissions of greenhouse gases by at least 5% from 1990 levels in the commitment period 2008-2012. The EU has agreed to reduce its combined emissions by 8% below 1990 levels. This will be achieved by means of a so-called 'bubble', designed to allow the EU's target to be redistributed between the Member States to reflect their national circumstances, their requirements for economic growth and the scope each has for further emission reductions.

Under the Protocol, reductions in greenhouse gases made by removals from sources or through the employment of sinks, must be accounted for in a transparent and verifiable manner. The requirement to record removals and reductions in this way is partly based upon concerns about the permanence of storage techniques. In the absence of strict accounting mechanisms, once a credit has been awarded, there is little incentive to ensure the containment of a gas or to minimise its escape. Reductions made by CCS have raised concerns, because there remain issues regarding the security of stored CO_2 and possible leakages.

In 2011, the Conference of the Parties serving as Meeting of the Parties to the Kyoto Protocol adopted a decision to include CCS within the list of activities eligible under the Clean Development Mechanism (known as CDM). This means that CCS activities meeting the requirements established by such rules and procedures will be able to generate Certified Emission Reduction (normally referred to as CER) units - the carbon credits produced by CDM projects - to account against Annex I mitigation targets under the Kyoto Protocol (CMP.6) (CMP.7).

2.2.4 Directives and regulations relating to offshore CO_2 storage

2.2.4.1 International offshore CO_2 storage legislation

There are three main international agreements regarding the protection of the marine environment which affects the CCS activities and site operation. The United Nations Convention on the Law of the Sea (UNCLOS) of 1982 is a framework agreement which provides protection to all marine areas; the London Convention of 1972 and its superseding London Protocol of 1996 were created to protect the marine environment and prevent pollution caused by the dumping of waste.

London Convention

The Convention entered into force in 1975 and was the first international agreement to provide protection to the marine environment from the deliberate disposal at sea of wastes and other matter.

In the 1990s, Contracting Parties to the Convention decided that the Convention required modernisation, and a new approach to waste management at sea was developed in the form of the 1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Protocol).

London protocol

Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1996 (IMO, 1996, “London Protocol”) aims to create a more modern and comprehensive waste management system for the seas than the one established under the 1972 London Convention (IMO, 1972), with a heightened emphasis upon the protection of the environment. Following the Protocol's entry into force and various legal and technical reviews, Australia, co-sponsored by France, Norway and the United Kingdom, submitted a proposal to amend Annex 1 in order to allow the storage of CO_2 in sub-seabed geological formations.

The new Protocol amendment has inserted an eighth category into the Annex 1 list of wastes and other matter that may be considered for dumping. This category consists of 'carbon dioxide streams from carbon dioxide capture processes for sequestration'. Further clarification is provided by way of a new subsection 4, which details the circumstances under which these CO_2 streams may be considered for dumping, as follows:

- disposal is into a sub-seabed geological formation; and
- they consist overwhelmingly of carbon dioxide (they may contain incidental associated substances derived from the source material and the capture and sequestration processes used); and

- no wastes or other matter are added for the purpose of disposing of those wastes or other matter (Annex 1, subsection 4).

There are still some issues to be decided within the protocol. One, and probably the most important, is related to the transboundary movement of CO_2. The amendment to Article 6 is significant not only because it allows for transboundary transport of CO_2 for geological disposal under the Protocol, but also because it requires that it is accompanied by transparent distribution of responsibilities between the countries involved (either Contracting or non-Contracting Parties to the Protocol) and by a level of environmental protection comparable with the one ensured by the Protocol. This would entail that the permitting process, risk assessment and environmental impact under the Specific Guidelines must be included in the export agreement or arrangement referred to in the revised Article 6.

Despite its importance for the development of CCS, the amendment to Article 6 has not yet entered into force and there is currently little indication that a sufficient number of Contracting Parties will ratify it in the near future. This means that, until the ratification and entry into force of such an amendment, transboundary transport of CO_2 for the purpose of geological disposal will still be prohibited under the Protocol. This situation has a direct impact upon the future development of CCS transboundary activities.

UNCLOS

The United Nations Convention on the Law of the Sea (UNCLOS, 1982) entered into force in 1994 and was established to provide an overarching international agreement regulating the various uses of the world's oceans and seas. The scope of the Convention is very broad and provides what has been termed a 'constitution for the oceans', covering the utilisation of resources, shipping, marine research, the exploitation of the exclusive economic zone and continental shelf, and the prevention and avoidance of marine pollution. The Convention contains broad principles and provisions, allowing its Contracting Parties to create more precise national regulations with regard to the marine environment.

There are some key legal issues concerning CCS in the UNCLOS. First, UNCLOS does not expressly prohibit CCS activities, but its provisions may well have an impact where the activities are deemed to constitute pollution, which is defined in Article 1(4). There is no conclusive opinion as to whether CCS would constitute pollution in accordance with the definition. Secondly, UNCLOS applies to the seabed and its subsoil. However, there remains uncertainty as to whether its provisions would apply in order to regulate CCS activities undertaken beneath the subsoil. Under the provisions of UNCLOS, the transport of CO_2, by ship or pipeline, to an injection platform could be considered as dumping and subject to the requirements of the London Convention. The London Convention of 1972 (IMO, 1972) and the later Protocol of 1996 (IMO, 1996) contain global rules and standards with regard to dumping and marine pollution.

2.2.4.2 European

The OSPAR Convention (2007c) is the main legal framework governing the protection of the marine environment in the North-East Atlantic and North Sea. The EU (initially as the European Community) and 15 individual states (mainly EU Member States) are Contracting Parties to the Convention. Parties to the OSPAR Convention may also be contracting parties to other international marine conventions, which themselves have a bearing upon the legality of CCS activities.

OSPAR, in its original form, contains several provisions that obstruct the employment of CCS technologies. Recent amendments to the Convention, however, bring it into line with the provisions of the London Protocol and allow for the sequestration of carbon dioxide in sub-seabed geological formations (subject to fulfilment of certain conditions). These amendments have now entered into force for several Contracting Parties who have completed the relevant ratification process in accordance with the Convention's provisions.

The Marine Strategy Framework Directive is a European Union law that supports OSPAR and other international and regional marine agreements by compelling EU Member States to carry out a series of measures aimed at achieving 'good environmental status' by 2020.

The EU Directive on the geological storage of carbon dioxide (Directive 2009/31/EC) also applies to offshore CO_2 storage in member states' offshore territory.

OSPAR

Convention for the Protection of the Marine Environment of the North East Atlantic, 1992 (OSPAR) entered into force on 1998. In June 2007, the OSPAR Commission adopted amendments to the Convention to allow for the storage of CO_2 in geological formations under the seabed. The Commission further decided to legally rule out the placement of CO_2 into the water column of the sea and on the seabed because of 'potential negative effects'. These amendments will not come into force until the ratification process is completed in accordance with the Convention's provision.

Amendments to Annex II and Annex III

The contracting Parties to the Convention made amendments to both Annex II and Annex III, by introducing new paragraphs. In Annex II, a new sub-paragraph is added to Article 3(2) which reads:

"(f) carbon dioxide streams from carbon dioxide capture processes for storage, provided:

- disposal is into a sub-soil geological formation;
- the streams consist overwhelmingly of carbon dioxide. They may contain incidental associated substances derived from the source material and the capture, transport and storage processes used;
- no wastes or other matter are added for the purpose of disposing of those wastes or other matter;
- they are intended to be retained in these formations permanently and will not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area."

This amendment includes CO_2 in the list of wastes or other matter that may be dumped in the marine environment, provided the CO_2 streams which are stored in this manner meet the other preconditions listed in subsections (i) to (iv). Stored CO_2 streams may only be stored in accordance with an authorisation issued by the Parties' relevant authorities and carried out in accordance with their regulation. These authorisations and regulations must in turn be 'in accordance with the relevant applicable criteria, guidelines and procedures adopted by the Commission (Article 4.1, Annex II).

Annex III is also amended to accommodate CCS technologies: two new paragraphs are included under Article 3. The new paragraphs 3 and 4 provide:

"The prohibition referred to in paragraph 1 of this Article does not apply to carbon dioxide streams from carbon dioxide capture processes for storage, provided:

- disposal is into a sub-soil geological formation;
- the streams consist overwhelmingly of carbon dioxide. They may contain incidental associated substances derived from the source material and the capture, transport and storage processes used;
- no wastes or other matter are added for the purpose of disposing of those wastes or other matter;
- they are intended to be retained in these formations permanently and will not lead to significant adverse consequences for the marine environment, human health and other legitimate uses of the maritime area."

The Contracting Parties shall ensure that no streams referred to in paragraph 3 shall be disposed of in sub-soil geological formations without authorisation or regulation by their competent authorities. Such authorisation or regulation shall, in particular, implement the relevant applicable decisions, recommendations and all other agreements adopted under the Convention.

This amendment provides an exception for CCS activities from the prohibition contained in Annex III, with regard to the dumping of wastes or other matter from offshore installations. However, these activities are required to meet the preconditions listed in sub-sections (a) to (d) and be stored in accordance with the relevant authority's authorisations and regulations.

OSPAR Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations

At the meeting of the OSPAR Commission in June 2007, a further decision was adopted with regard to the regulation of the storage of CO_2 in geological formations. The decision (Decision 2007/2, OSPAR, 2007b) stated that the Parties' competent authorities are responsible for ensuring the correct regulations and authorisations are in place for CCS activities, and that these regulations and authorisations are made in accordance with the OSPAR Guidelines for Risk Assessment and Management of CO_2 Streams in Geological Formations ('the Guidelines') (OSPAR, 2007a).

Marine Strategy Framework Directive

The Marine Strategy Directive (MSD) is the first piece of EU legislation designed to tackle the marine environment in a direct and comprehensive way. The Directive (EU CCS Directive 2008b) establishes a framework within which Member States are to take measures to achieve or maintain good environmental status in the marine environment by the year 2020 at the latest. The Directive makes no direct reference to CCS activities; however, it applies specifically to the sea-bed and subsoil, so is relevant for major CO_2 transport and storage projects at sea. Marine CCS activities potentially fall within the definition of pollution under Article 3(8); this will depend on whether they are deemed to result or be likely to result in deleterious effects (Directive 2008/56/EU).

2.2.4.3 National regulations

UK

The Marine and Coastal Access Act (2009) expressly excludes carbon dioxide storage activities from the requirement of obtaining a marine licence, as they are governed by the licensing requirements of the Energy Act (2008). However, a marine licence is still necessary for undertaking offshore CCS activities or related activities 'in, under or over any area of the sea which is within the Welsh inshore region or Northern Ireland inshore region'.

The Energy Act (2008) establishes a regulatory framework for the licensing of the offshore storage aspect of carbon capture and storage. The Act asserts the rights of the Crown to an Exclusive Economic Zone (EEZ) (200 nautical miles), in accordance with Part V of the United Nations Convention on the Law of the Sea (UNCLOS, 1982), for the 'storing of gas' (whether or not with a view to its being recovered). The government may also designate 'Gas Importation and Storage Zones' within the EEZ. For operators seeking to undertake CCS activities within the newly designated EEZ, a lease will be required from the Crown Estate. The Act introduces a detailed section relating to the enforcement of licences and criminal offences, and sanctions are introduced, in instances where activities are undertaken without a licence or where a licence holder fails to abide by its prescribed conditions. The licensing authority may make a direction requiring the licence holder to take any particular steps that it deems necessary; failure to comply with an order of this nature will be an offence. In order to assist in carrying out the functions described in the Act, inspectors may be appointed by the Secretary of State or Scottish Ministers.

Australia - Federal Legislation

The Australian Government has developed a regulatory framework for offshore CO_2 storage based on amendments to existing petroleum legislation. The framework was established under the Offshore Petroleum Amendment (Greenhouse Gas Storage) Act 2008, which amended the Offshore Petroleum Act

2006, now renamed as the Offshore Petroleum and Greenhouse Gas Storage Act 2006 (OPGGS Act). In addition to offshore petroleum activities, the OPGGS Act regulates certain offshore CCS activities, such as construction and operation of infrastructure facilities and pipelines for conveying GHG substances and injection and storage of GHG substances.

The Australian regulatory framework includes a set of regulations enacted under the OPGGS Act. In the Offshore Petroleum and Greenhouse Gas Storage (Environment) Regulations 2009 aim to ensure that any offshore petroleum or GHG activities are carried out in a manner consistent with the principles of ecologically sustainable development and in accordance with an environment plan. Offshore Petroleum and Greenhouse Gas Storage (Resource Management and Administration) Regulations 2011 was built to e.g. ensure that offshore operations are carried out in accordance with best practices for oilfield activities and compatible with the maximizing long-term petroleum recovery. It ensures also that the administrators of the OPGGS Act are informed in a timely manner of exploration, discovery, development, production and injection activities. Offshore Petroleum and Greenhouse Gas Storage (Greenhouse Gas Injection and Storage) Regulations 2011 detail the requirements for the following six elements related to injection and storage activities described in the OPGGS Act. The regulations detail the process around approval of a site plan as well as its contents. The site plan must contain predictions of the behaviour of the GHG substance to be stored. If the substance is found to not behave as predicted then the serious situation powers in the OPGGS Act will be triggered. The site plan must also cover risk assessment and monitoring activities. The regulations set out reportable incidents as any variations from the behaviour predictions in the site plan and any leakage from any wells that are part of the project.

Australia – State legislations

Victoria

The Victorian Government has enacted the Offshore Petroleum and Greenhouse Gas Storage Act 2010 (Victorian Act). The Victorian Act adopts the definition of a Commonwealth offshore area under the OPGGS Act and provides for a similar regulatory framework for offshore petroleum and GHG activities. The key difference between the Victorian Act and the OPGGS Act is in relation to long-term liability for GHG activities.

2.2.5 Directives and regulations relating onshore CO_2 Storage

2.2.5.1 European and regional

European Waste Legislation

The adoption, in April 2009, of the Directive on the geological storage of carbon dioxide (Directive 2009/31/EC) (the CCS Directive) clarified most of these questions by expressly excluding 'carbon dioxide captured and transported for the purposes of geological storage and geologically stored in accordance with' the Directive from the definition of 'waste' under existing waste legislation. This means that the main focus of regulation for CCS activities will be the specific provisions of the CCS Directive rather than the more general rules applying to wastes. The EU waste laws could still come into play, however, if CCS permit conditions are breached or if ancillary aspects of CCS operations either cause harm or involve handling of classified wastes.

Transfrontier Shipment of Waste Regulation

Transfrontier Shipment of Waste Regulation (Regulation No. 1013/2006) regulates the supervision and control of shipments of waste, within and into or out of the European Union, and implements the Basel Convention (1989 Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal). Article 36 of the Directive on the geological storage of carbon dioxide (2009/31/EC), adopted in April 2009, amends Article 1(3) of the Transfrontier Shipment of Waste Regulation to categorically exclude from the scope of the Regulation "shipments of CO_2 for the purposes of geological storage in accordance with" the CCS Directive. This means that, insofar as the shipment of CO_2 occurs in compliance with the provisions of the Directive, the Regulation will not apply to transboundary transport of CO_2 and, therefore, does not represent a potential obstacle or barrier to CCS activities.

Waste Framework Directive

Revised Waste Framework Directive (Directive 2008/98/EC, EU CCS Directive, 2008a) seeks to protect human health and the environment, against the damaging effects of the 'collection, transport, treatment, storage and tipping of waste' and to provide consistent regulation of waste disposal and recovery. Two aspects of CCS operations will remain subject to the waste regime: first, all handling of the numerous non-CO_2 substances and materials that fall within the definition of waste (amines, solvents, lubricants, metals, etc); and second, any CO_2 that escapes containment from approved CCS vessels or sites, whereupon it could be deemed waste under the principles enunciated in the Commune de Mesquer judgment of the European Court of Justice (see above). In the latter case, both the polluter pays and responsibility provisions, in Articles 14, 15 and 8 respectively, although relatively undeveloped at this stage, could in the long run have a bearing upon who is required to remedy the harm.

European Water Legislation

The 2000 Water Framework Directive (Directive 2000/60/EC) provides an umbrella for the larger part of EU water law. Member States are obliged to establish environmental objectives and river basin management plans for bodies of water within their jurisdiction, and to implement measures aimed at achieving good ecological, chemical and quantitative status of water bodies by 2015. The 2006 Groundwater Directive builds on the earlier provisions of the Water Framework Directive in relation to groundwater assessment and protection measures.

Prior to 2009, the Water Framework Directive would have prohibited the injection of CO_2 into groundwater for the purpose of CCS activities. With this in mind, the European Commission proposed an amendment to the Water Framework Directive to exempt CO_2 injection for CCS from certain restrictive provisions in the Directive. That amendment was then included in the 2009 Directive on the geological storage of carbon dioxide. The CCS Directive also requires that CO_2 injection is in compliance with the protection of groundwater provisions under both the Water Framework Directive and the Groundwater Directive.

Groundwater Directive

The Groundwater Directive (2006/118/EC) strengthens and builds on provisions contained within the Water Framework Directive (WFD) (2000/60/EC) relating to groundwater. While CCS activities would not seem to be primarily affected by provisions in the Groundwater Directive, which are more directly concerned with nitrates and pesticides, injection of CO_2 streams could potentially be regulated under Article 6(1)(b), were Member States to decide that CO_2 fell within the definition of 'hazardous substance'. However, Article 6(3)(a) of the Directive ensures that the exemptions given to particular activities in Article 11(3) (j) of the WFD also apply to the daughter provisions. This would include the amendment exempting CCS activities made to the WFD by the Directive on the geological storage of carbon dioxide (2009/31/EC).

Water Framework Directive

The Water Framework Directive (WFD) (2000/60/EC) is overarching legislation that will eventually replace a number of existing EC directives on water. CO_2 is not expressly included in the Annex VIII list of main pollutants. However, that list is only indicative and CO_2 could still be classified as a pollutant under the WFD under the more general definition given in Article 2 (31) ('... any substance liable to cause pollution ...'). If so its direct discharge into bodies of groundwater for storage would be prohibited by Article 11(3)(j).

2.3 Conclusions

When the injection period starts, the storage site is allowed to inject CO_2 within certain site-specific license conditions. The operation phase is considered vulnerable with respect to risks, as it may be the first time that CO_2 is injected to the selected formation and some unexpected events may happen. Risks can be classified to health, safety and technical risks in local environmental, general operational risks related to injection, operational risks related to the CO_2 stream composition and risks related to CO_2 stream pressure and temperature.

Considering legislation, operators are obliged mainly to monitor, report and allow inspections during the injection. There are some specific CCS dedicated legislations in act and also a number of international agreements and legislations, which are not directly related to CCS, but are relevant and should be used to guide the operations on- and offshore. These non-specific legislations may pose some problems for CCS activities, some pertinent questions have not been answered to this date and it is uncertain how these may affect possible CO_2 storage site projects. However, most of such legislations are being revised. At national level, most of the EU countries have transposed the EU CCS directive to national legislation; while the U.S, Canada and Australia have their own legislations on CCS and CO_2 geological storage.

3 POTENTIAL LEAKAGE EVENTS - RELATED REGULATIONS AND GUIDELINES

This chapter presents an overview of the international regulations and guidelines related to potential leakage events of CO_2 from a geological storage site, an overview of the international regulations and guidelines related to leakage, as well as the effects of CO_2 reaching the biosphere.

The chapter starts with a review of the main international acts and agreements that regulate the risk of CO_2 leakage, the London Convention and Protocol, OSPAR, EU Directives on Geological Storage of CO2 and ETS. These international agreements were elaborated at different times and differ mostly on their focus (e.g. OSPAR focuses only on the effects of CO_2 leakage in the marine environment whereas EU Directive on Geological Storage of CO_2 refers to CO_2 leakage in all environments) and geographical coverage (although they overlap to some extent with regards to this). Still, all regulations require that storage operations are conducted in a safe manner, taking corrective measures in case of leakage. For this reason, they also stipulate the necessity of conducting a thorough risk assessment in each step of a storage project (starting with the pre-operational phase) in order to prevent and mitigate the identified hazards.

In this context, another important part of the chapter refers to guidelines for risk assessment, especially the ones developed under OSPAR (FRAM) and EU CCS Directive (Guidance Document 1). These guidelines comprise several stages for risk assessment, covering the entire cycle of a CO_2 storage project, starting from site characterisation to risk management (including monitoring and corrective measures).

A first step in the risk assessment for a CO_2 geological storage site is to identify all of the potential risks related to the site, especially the potential leakage pathways, presented within this chapter, such as permeable caprock, faults and fractures, wells and other anthropogenic pathways (e.g. hydraulic fracturing of reservoir possibly connected to a CO_2 storage site or extension of fractures to the CO_2 storage complex).

The final part of the chapter presents the effects of a potential CO_2 leakage on the environment and on human safety and health through a few studies made on this topic using natural analogues (e.g. Laacher See, Germany; Panarea Island, Italy) and some incidents and regulations related to human and animal exposure to increased levels of CO_2. Although the exact effects of a CO_2 leakage are not yet known (as the composition of CO_2 stream and the re-actions of co-injected elements play an important role in this issue and there is still a research need for controlled CO_2 leakage), it is commonly accepted that CO_2 leakage can cause acidification of sea or groundwater, mobilisation of toxic elements (due to pH change in soils), adverse effects on plants, animals and humans.

The risks of leakage are regulated through several acts and international agreements such as the London Convention and Protocol, OSPAR, EU directives on Geological storage of CO_2 and the ETS Directive. The regulatory regimes require that storage operations are conducted in such a manner that any hazards are prevented or mitigated and also that necessary corrective measures must be taken in the case of leakage.

According to the EC directive a storage site shall not be chosen if there is significant risk of leakage of the stored CO_2.The risk of leakage from a site with a storage permit has therefore been restricted and the site conditions delimited from the very beginning. Site characterisation is the first step in the process of choosing the most appropriate storage site with no significant risk of leakage. During this process all potential leakage pathways should be identified and their implications then assessed during the risk assessment process. The risk analysis is a major part of this assessment process and is important when deciding on an appropriate storage site.

The second step in leakage prevention is the implementation of a comprehensive, site-specific monitoring plan covering the storage site and the surrounding area (including the seal and overlying marker formations) (i.e. the storage complex). The main purpose of monitoring is to permit control of the CO_2 plume behaviour and to discover and prevent any potential leakage at an early stage. The data acquisition performed during monitoring will also provide new high quality information that will continuously improve the static and dynamic characterisation of the storage complex. Further details on monitoring can be found in CGS Key Report 1 (Rütters *et al*., 2013).

The effects of CO_2 reaching the biosphere are not yet fully understood. However, it is widely known that CO_2 leakage may cause acidification of sea water, groundwater resources and soils. The change in pH also mobilises environmentally toxic elements in soils such as lead. An important issue with respect to the effects of leakage is the composition of CO_2 stream and the reactions of the co-injected substances. There are many lessons to be learned from natural analogues of CO_2 leakage and from laboratory experiments as well as the catastrophic events of Lake Nyos and Monoun in Africa which demonstrated the importance of understanding potential hazards in order to mitigate them fully.

3.1 International agreements regulating CO_2 leakage

There are several national and international regulatory regimes that currently cover the impact of a leakage event from a geological CO2 storage site. These include the London Convention and Protocol, OSPAR and EU directive which are discussed next. The geographical coverage of these regulatory regimes overlap to some extent. These international agreements were also elaborated at different times and from different starting positions, reflected by their content and focus, i.e. OSPAR is concerned with effects on the marine environment, whereas the EU CCS Directive is more general in its expression.

3.1.1 London Convention and Protocol

The London Convention and Protocol is administered by The International Maritime Organisation, which has 170 member states and three associated members. The full name of the convention is “Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter” (IMO, 1972). The London protocol is part of the modernisation process of the convention. It was adopted in 1972 and entered into force in 2006, and will eventually replace the convention. As of January 2013, according to the IMO website (accessed 2013-01-28), the London Protocol had 42 contracting states and the London convention had 87 contracting states all over the globe. From 2007 onwards, CO_2 streams appeared on the list of substances that are allowed to be dumped in the maritime area if a) they are disposed into a sub-seabed geological formation, b) the CO_2 stream consists overwhelmingly of CO_2, and c) no wastes are added for the purpose of disposing those wastes. Due to its broad international coverage, currently the London Convention is one of the best available regulatory instruments regarding CO_2 storage.

The Protocol itself does not directly cover issues concerning leakage of CO_2 from an off-shore site where geological storage site of CO_2 has been undertaken. The London Convention and Protocol, including amendments for permitting the CO_2 storage in the sub-sea beds, solely regulates between parties their responsibilities/liabilities of an eventual pollution (polluter must pay) and the obligations of issuing special permits for dumping permitted substances and materials into the sea or sub-seabed, to “keep records of the nature and quantities of all matter permitted to be dumped and the location, time and method of dumping” (Article VI.c. from the London Convention, 1972) and “to monitor individually, or in collaboration with other Parties and competent international organizations, the condition of the seas" (Article VI.d. from the London Convention, 1972) for the enforcement of the Convention.

3.1.2 OSPAR Convention

The OSPAR Convention (The Convention for the Protection of the marine Environment of the North-East Atlantic) has published guidelines concerning risks related to storage of CO_2 in off-shore geological formations in the north east Atlantic (OSPAR Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formation reference number, 2007). Countries that are parties of OSPAR include Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom, together with the European Community. The guidelines have been ratified by Norway, Germany, the United Kingdom, Spain, European Union, Luxembourg, Denmark and the Netherlands (July 2011).

The OSPAR guidelines only consider storage related CCS issues. The guidelines have been designed to ensure that if leakage does occur from a site of geological storage of CO_2, "it does not lead to significant adverse consequences for the marine environment, human health or other legitimate uses of maritime the area". OSPAR recognises that leakage of CO_2 into the marine environment may occur during injection and/or from the storage site after injection. In general the guidelines aim to aid and facilitate the management of a CO_2 geological storage site so that:

- The suitability of a potential site is properly assessed and necessary measures of hazard reduction, remediation and mitigation are identified.
- Risk characterisation to the marine environment is undertaken for each potential storage site.
- Monitoring is performed and a strategy to manage uncertainties and minimise risks is developed.

The guidelines also include a framework for risk assessment and management of a geological CO_2 storage site, also referred to as FRAM which is an integral part of the OSPAR guidelines. FRAM also considers developments of the London Protocol.

FRAM presents all the possible impacts of an eventual leakage in the marine environment. Section 1 of FRAM introduces a conceptual model of potential environmental pathways and effects (Fig. 3-1) to be considered for the risk assessment and management of offshore storage sites. Appendix 1 of FRAM includes all the relevant information needed for risk assessment and management, while Appendix 2 identifies the issues that need more research. OSPAR-FRAM (2007) Appendix 3 classifies leakage as "the escape of that CO_2 stream from the storage formation into overlying formations, the water column and the atmosphere".

3.1.3 European Union Directive - Geological storage of CO2

The EU CCS directive (Directive 2009/31/EC) was published in 2009 and should have been fully transposed by the member states by June 2011. In connection with the implementation of the directive, the Commission produced four guidance documents in order to facilitate and aid the member states during the national implementation processes. These are herein referred to as GD1 (EC, 2011a), GD2 (EC, 2011b), GD3 (EC, 2011c) and GD4 (EC, 2011d).

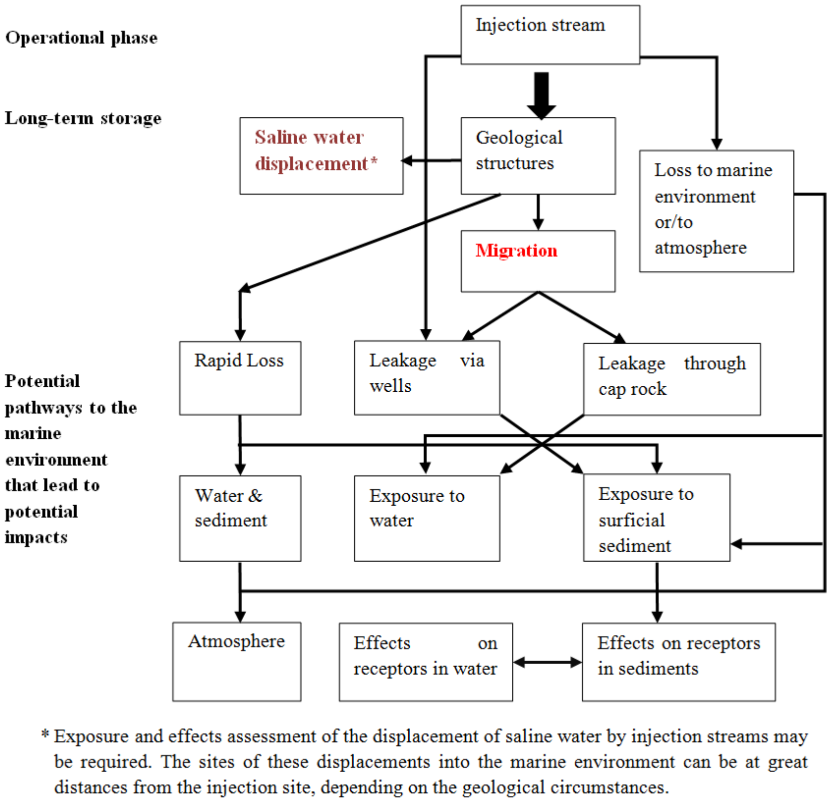

Fig. 3-1: Conceptual model of potential environmental pathways and effects (OSPAR-FRAM, 2007).

Following the directive, leakage is defined as any release of CO_2 from the storage complex and is mainly mentioned in Article 16 – "Measures in case of leakages or other significant irregularities" and Annex 1, step 3 "Characterisation of the storage dynamic behaviour, sensitivity characterisation and risk assessment". The directive makes it clear that member states are responsible for ensuring that if leakage or any other significant irregularity occurs, the operator informs the competent authority (hereafter referred to as CA) and that the operators takes the necessary corrective measures including those related to the protection of human health. The operator must also notify the CA "in cases of leakages and significant irregularities which imply the risk of leakage".

To ensure that leakage events have been accounted for in the planning process of a geological storage site of CO_2, the operator has to include a proposed corrective measures plan in the storage permit application. The corrective measures plan is included in the final storage permit and the operator is required to notify the CA in case of leakage or significant irregularities. The storage permit will also state that the operator has to implement the proposed corrective measures plan in case of leakage or any other significant irregularities. If the operator fails to do so, the necessary measures should be taken by the CA, and the costs then recovered from the operator.

3.2 CO_2 storage risk assessment

There are several recently published studies and recommendations concerning risk analysis of CO_2 storage (e.g. OSPAR-FRAM 2007, EU CCS Directive 2009, USA Energy Department 2011, CO_2Care 2011, MUSTANG 2012).

The prerequisite for establishing a CO_2 storage site is that no significant leakage will occur from the storage complex, and the risk assessment process is vital in order to ensure this requirement is satisfied. Therefore it is important to begin the risk assessment process early in the project, simultaneously with site characterisation of the storage complex. It must also be presented to the licensing authorities before a storage permit can be issued. A well-considered risk assessment includes all sorts of risk events that may occur at the storage site, from leakage of CO_2 into the atmosphere to problems with the injection equipment and general health and safety issues. In this section the aim is to focus on risks relating to the geological issues of a storage project.

The risk assessment should include information about the CO_2 injection, historical description of the oil/gas field if CO_2 storage is implemented in connection with EOR, location of active and abandoned wells in relation to for instance, groundwater supplies, lakes, homes and infrastructure, the condition of existing wells, qualitative assessment of the geological modelling results from the site characterisation, etc. The risk assessment may also be used as a tool in the communication plan in order to increase public understanding and acceptance of the project.

Both OSPAR and the EU CCS Directive provide frameworks regarding the risk characterisation and risk assessment processes of a geological CO_2 storage site. These are briefly described below.

3.2.1 Risk assessment under the OSPAR Convention

The FRAM of the OSPAR guidelines (2007) recommends that the risk assessment is undertaken during the entire life cycle of a CO_2 storage project. The FRAM includes six stages covering the life cycle of a CO_2 storage site, and the risk characterisation is one of these stages:

- Problem formulation,
- Site selection and characterisation,
- Exposure assessment,
- Effects assessment,
- Risk characterisation,
- Risk management (including monitoring and mitigation).

During the problem formulation stage, data, including geoscientific data, is collected for use in the conceptual modelling of the storage site. The results from the modelling will be used later on in the site-specific risk assessment. Issues that are addressed during this first stage include a) the suitability of the proposed formation as a CO_2 storage site, b) the nature of overlying bedrock c) the potential mobilisation of substances directly or indirectly connected to the CO_2 stream, d) the characteristics of the marine environment above and around the storage site and e) records associated with the authorisation and licensing of a geological storage of CO_2 which need to be maintained during a longer period of time than is usual in authorised practises.

The outcome of the site selection and characterisation process will be an assessment of the storage capacity of a specific storage site. It should demonstrate that the characteristics of the site enable safe long-term storage of CO_2 so the marine environment and future uses of the maritime area are protected. The results should also establish a baseline for storage site management and monitoring during the injection and post-injection period. In the Appendix 1 of Annex 1 (a summary is presented in Table 3-1), the issues that may be considered during in the risk assessment and management process are specified. The guidelines also provide examples of the relevant parameters that should be identified, qualified and quantified in the risk assessment process. Many of these parameters are collected during the site selection and characterisation process.

Tab. 3-1: A summary of Appendix 1, OSPAR Guidelines for Risk Assessment and Management of Storage of CO_2 streams in Geological Formation reference number 2007-12 (after OSPAR, 2007).

Issue	**Examples of parameters**
Characterisation of the CO_2 stream	Type and properties of other substances Concentration of other substances
Location and geographical factors	Water depth Formation depth Human health and safety
Existence of amenities, biological features, and legitimate uses of the maritime area	Areas of special ecological, economical and scientific importance
Regional geological setting	Regional geoscientific information
Historical uses of the area	Man-made structures, e.g. wells
Reservoir/seal evaluation	Geological, geophysical, geochemical and geomechanical characteristics of the reservoir and seal.
Marine environment characterisation	Ocean current, sea floor topology Physical, chemical and biological characteristics of the seabed, sediments and overlying waters.
Economic/regulatory factors	Economic feasibility including impact on other sea-bed resources Regulatory framework

The exposure assessment characterises the potential effects of leakage on the marine environment, human health and other legitimate uses of the maritime area. This additional information can be used in the wider risk assessment and risk mitigation process.

The assessment of the effects of CO_2 storage describes the expected consequences of storage at a specific site. A prerequisite for storage is that no significant leakage will occur, however, the effects assessment should demonstrate that, if leakage from a storage site should occur, there is no significant harmful consequence to the marine environment, human health and other legitimate uses of the maritime area.

The outcome of the risk characterisation is an "Impact Hypothesis". It is a statement describing the expected consequences of geological storage of CO_2, which can be used to reject or approve a proposed storage site and to define monitoring requirements from an environmental point of view.

The purpose of the risk management plan is to ensure that geologically stored CO_2 is retained within the storage site and to minimise the effects of possible leakage events including of incidental associated substances and substances that have been mobilised by the CO_2 stream.

3.2.2 Risk assessment in the EU CCS Directive

In the EU CCS Directive, the risk assessment processes is a part of the site characterisation and assessment of the potential storage complex described in article 4(3). Hence, it is a mandatory task in the planning process for a geological storage site of CO_2 and the risk assessment must be a part of the storage permit. Following the EU CCS Directive, the risk assessment include:

- Hazard characterisation,
- Exposure assessment,
- Effects assessment,
- Risk characterisation.

The aim of the hazard characterisation is to test the security of the storage complex. Therefore, the entire range of operating conditions must be covered. Issues to consider are potential leakage pathways, potential magnitude of different leakage events, critical parameters that affect potential leakage, secondary effects of CO_2 storage and any factors that could pose a hazard to human health or the environment. Examples of critical parameters are maximum reservoir pressure, maximum injection rate and temperature. Amongst the secondary effects of CO_2 storage are displacement of formation fluids, new minerals and other substances created by storing CO_2.

The exposure assessment concerns the environment and human activities on top of the storage complex. The assessment should also include how CO_2 reacts when it reaches the ground or seafloor.

The effect assessment comprises the effects of leaking CO_2, including impurities from the injected CO_2 stream or substances that have formed in the storage reservoir, to the biosphere. It is based on how sensitive species, communities and habitats are to CO_2 and other potential substances co-injected with CO_2 or mobilised/formed as a result of CO_2 reactions with fluids or mineral matrix within the storage complex.

The risk characterisation is the assessment of the short- and long-term safety and integrity of the storage site and is based on the hazard, exposure and effects assessments. It assesses the risks of leakage and includes the worst-case scenarios of leaking CO_2 and the effects to the environment and to health. Sources of uncertainties are also included in the assessment and a description of the possibilities to reduce uncertainties should be included.

3.3 Leakage pathways

Five different leakage events are identified in Guidance Document 1 of the EU CCS Directive. These include caprock deficiency, faults and fractures, structural spill of the trap, updip leakage through high permeable intervals and transport of dissolved CO_2 out of the storage complex. These are all very different in nature and are effects of the geological and anthropogenic conditions of the storage complex. There is, therefore, no single solution to all these possible leakage events, hence the importance of treating each possible leakage event separately.

Not all potential leakage scenarios will be relevant to the various geological storage options of CO_2, since the trapping mechanisms of CO_2 are different depending on the geological conditions of the chosen storage site. Within the FRAM, potential leakage pathways have also been identified and their potential impacts during the life cycle of a storage project have been delineated (Fig 3-1).

Leakage can be predicted and also possibly avoided using numerical modelling, and flow modelling in particular, of the storage complex. The many processes, e.g. hydrogeological and geochemical processes, acting within a reservoir, are commonly interlinked and dependent on each other. Therefore, all dependent processes must be considered during modelling in order to create the most accurate model, including rock property data, e.g. porosity, permeability, relative permeability, capillary pressures, fluid saturation and mineralogy. A list of different numerical codes that are used in modelling are listed in NETL (2011).

There are technologies to be used in order to avoid leakage, and decrease the effects of potential leakage from a geological storage of CO_2. Benson and Hepple (2005) summarised a number of actions that can be taken to mitigate leakage from the storage reservoir in different scenarios. As the nature of a geological storage of CO_2 is that it is defined by natural geological boundaries, these are not likely to be “fixed” if leakage occurs. Therefore leakage remediation actions are about controlling the CO_2 within the storage reservoir and surrounding formations. Controlling actions include reduction of pressure within the storage reservoir, increasing the pressure in the geological formation into which CO_2 is leaking and interception and extraction of the injected CO_2 before it leaks out of the storage reservoir.

3.3.1 Permeable caprock

The caprock is the impermeable part of the storage complex which will prevent CO_2 from migrating and finally leaking out into the atmosphere or oceans. Leakage may occur through the caprock if its physical properties, such as permeability, have been underestimated, or if new faults and fractures have been created, cutting through the caprock, or if pre-existing faults and fractures have been reactivated.

Methods for conceptual models of the cap rock have been present within the hydrocarbon industry since the 1950s. These have been applied to hydrocarbon reservoirs in order to estimate the caprock ability to retain hydrocarbons within the reservoir (e.g. Watts, 1987; Weber, 1997), and they can also be used to assess the ability of the caprock to retain CO_2 within a storage site. Therefore, caprock properties should be known adequately if the storage site is a depleted oil and gas field or if CO_2 storage is used in connection with enhanced hydrocarbon recovery. However, this is most likely not the case if the storage site is a deep saline aquifer or coal seam (Wo *et al*., 2005), since the caprock of those potential types of storage sites has not been studied for exploration purposes.

3.3.2 Faults and fractures

The site characterisation should include mapping and modelling of existing faults and fractures of the storage complex in order to determine what impact these structures may have upon the integrity of a particular storage site. Migration of fluids and gases can only occur through open fractures; hence it is vital to know whether existing fractures are open or closed, the size of fracture aperture(s) and the morphology of the fracture(s).

Good knowledge of the geological history of fractures and faults in the area, i.e., if they have been open or closed during geological time, will aid understanding of the geological development and will facilitate the assessment of the potential storage site. It is also important to evaluate the stress field of the bedrock at the storage site since this will impact on how these fractures and faults will behave during changes in stress field conditions. Changes in the local stress field may be caused by tectonic processes or affected by human activities, for instance drilling or injection (Smith *et al*. 2011a), and affect the behaviour of existing faults and fractures or create new ones. Knowing the geological history of exiting fractures and faults, facilitates the prediction of how the CO_2 plume at the storage site will behave during changes in the bedrock stress field.

Faults may function as natural limits of a storage site. However, if a fault through the caprock is reactivated during a large earthquake, or a series of earthquakes, these delimitations may not be as valid as first believed and leakage may occur, either through the fault itself or via permeable rocks on top of the reservoir that have become accessible through fault displacement. It has been demonstrated that fracture morphology is important in order to understand the fluid flow mechanisms within a low permeable carbonate caprock since the cubic law, which is commonly used to model fluid flow through single fractures, may be too simplistic to provide accurate results during modelling (Ellis *et al*., 2011). Ellis and co-authors demonstrated how acidified brine affected the fracture wall surface. In their study, wall roughness and fracture aperture were increased due to the dissolution of calcite, whereas neither dolomite nor clay/quartz/K-feldspar are affected to the same extent. Hence, clay mineral content is important when assessing the integrity of a carbonate rich caprock.

Fracture network modelling is another approach that has been used at In Salah (Smith *et al*., 2011), Otway (CO2CARE EU projetc) and the Blake field (SiteChar EU project) and to evaluate the effects of fracturing and geomechanical failure, with respect to the risk of migration of CO_2 through the caprock. In addition monitoring of microseismic events (Verdon *et al*., 2013) can be used to evaluate the risk of fracturing and potential fault reactivation due to CO_2 injection.

3.3.3 Wells

Wells are known possible anthropogenic leakage pathways from a CO_2 storage site. In the risk assessment and site characterisation process it is, therefore, vital to have identified all existing wells within the storage complex and assessed their integrity. Wells may have been drilled for different purposes, e.g. shallow water wells, energy wells, research boreholes, hydrocarbon production wells. There may also be wells that have been abandoned for a long time where the original purpose is unknown. Active wells are more easily accessible than closed wells and data are more easily obtained from them, facilitating the assessment of well integrity.

Active wells are also more easily adapted to enable safe injection of CO_2 and safe abandonment tailored to the conditions required by the CO_2 storage. Abandoned wells may lack much of the data that are needed in order to undertake an assessment of the well integrity, depending on, for instance, the age of the well, when it was abandoned and the archiving procedures of the responsible company. It is also a more expensive operation to remediate an abandoned well.

Carbon dioxide may affect wells in different ways. It has corrosive effects on steel, which may cause leakage through the steel casing. CO_2 causes chemical degradation of the cement plug that is used to close the well, hence the permeability and porosity of the cement may change and the risk of leakage may increase. A review of different laboratory studies testing the chemical degradation of well cement was presented by van der Kuip *et al.* (2011). Their comparison suggests that penetration of CO_2 into the cement in general is less than 1 m after 10 000 years. Water-saturated supercritical CO_2, in contrast to dissolved CO_2, increased the degradation rate of the cement, which was also the case when the cement was exposed to CO_2 under high temperature and low pH under experimental conditions. The higher temperature conditions (204 °C at 69 bar), resulted in a maximum of 12.4 m degradation of the cement plug after 10,000 years. The studies referred to in van der Kuip *et al.* (2011) show that the degradation mechanism is most likely defined by diffusion processes and the authors confirm that potential leakage of CO_2 through an abandoned well, most likely will not occur through chemical degradation of the cement plug.

Well integrity is also affected by the development of fractures in the cement plug. Similar to fractures in the caprock, these fractures also have to be considered as potential leakage pathways. Fractures in the well cement can develop through either natural or man-made changes in the stress field of the surrounding bedrock. Other features affecting well integrity are the degree of precision during placement of the cement plug and shrinkage of the cement. Both processes may cause leakage pathways between the cement and the wall of the well. However, these are of site-specific characteristics and need to be considered during the site characterisation process and risk assessment of each individual storage site.

Carbon dioxide leakage from wells is most likely the least expensive and easiest type of leak to stop. Repairing wells that do not function is routine work within the oil and gas industry and natural gas storage sites and there are several techniques that can be used to stop a well leaking CO_2 (Benson and Hepple, 2005). These include for instance replacement of injection tubes and packers if these fail and if leakage occurs between the casing and borehole wall, the cavity can be filled with cement. If a well is considered to be irreparable, the well is plugged with cement and abandoned.

3.3.4 Other anthropogenic leakage events

Hydraulic fracturing is a method which is commonly used in shale gas production and is also used in methane production from coal seams (e.g. Wo *et al.*, 2005). The method is applied to artificially create fractures in the reservoir rock (in that case a shale or coal seam) in order to increase its permeability. The risks of fracturing in relation to geological storage of CO_2 are somewhat different in the two applications. These are therefore treated separately below.

It is possible that the reservoir of a shale gas producing geological unit is part of the caprock of a geological storage of CO_2. Hydraulic fracturing in connection to shale gas exploration and extraction is an example of conflict of interest since hydraulic fracturing will increase the permeability of the caprock.

Therefore, an increased risk of leakage from the CO_2 storage site might be expected, if there is gas shale production in the caprock.

Methane production and/or geological storage of CO_2 in deep coal seams may include fracturing of the coal bed in order to increase the permeability. During this process there is a risk that fractures could extend into the caprock, decreasing cap rock integrity. However, hydraulic fractures are artificially created, and their extension can therefore to some extent be controlled. The vertical extension of hydraulic fractures is dependent on in-situ stress state of the bedrock, elastic moduli of the bedrock, fracture toughness, formation leak-off pressure and fluid flow. The growth of vertical fractures can be modelled using linear elastic fracture models and the risks can be reduced if the propagation of the fractures can be monitored (Wo *et al*., 2005).

During methane production, methane is desorbed from the coal. This process may cause shrinkage of the coal reservoir volume and affect the overlying bedrock integrity (Wo *et al*., 2005), which may either be the caprock of a coal seam CO_2 storage site or form part of the sealing formations for CO_2 storage in, for instance, a deep saline aquifer.

If the amount of injected CO_2 is greater than the storage capacity of the reservoir, dissolute CO_2 may be transported from the storage complex by natural fluid flow to areas where the geological conditions are less well known and potential leakage pathways may not have been identified. This migration event may happen if storage capacity of the reservoir has been grossly underestimated during the initial site characterisation process. However, a well-functioning monitoring program during injection will detect if the movements of the CO_2 plume goes beyond the anticipated reservoir and injection can be stopped. The CGS Europe Key Report 1 provides an extensive review of monitoring techniques. However, it should be noted that through the detailed geoscientific surveys undertaken during the site characterisation stage of the storage life cycle, storage capacity and the minimum capacity in particular should be well known so migration out of the storage complex should not occur.

3.4 Effects of CO_2 leakage

3.4.1 Effects of leakage of CO_2 into the groundwater

The leakage of CO_2 or the displacement of brine into a groundwater aquifer produces significant changes in groundwater chemistry and quality and may also cause physical impacts by interfering with groundwater extraction procedures when a large plume of gaseous CO_2 is involved (Esposito and Benson, 2011). The contamination of groundwater with CO_2 would lead to the formation of carbonic acid, which causes a decrease of pH, enabling dissolution of carbonate minerals and mobilisation of trace chemicals.

For the Zero Emission Research and Technology (ZERT) experiment in Montana, USA, food grade CO_2 was injected over a period of one month during which an intensive monitoring program, including water sampling, was performed. This experiment revealed significant changes in chemical parameters measured at the site, including a relatively rapid decrease of pH (7.0 to 5.6), increase of alkalinity (400 to 1,330 mg/l as bicarbonate, HCO_3^-), and electrical conductance (600 to 1,800 lS/cm) and an increase of natural trace chemicals (lead, arsenic, benzene) content following CO_2 injection (Kharaka *et al*., 2010). The increased levels of contaminants in the groundwater could pose a serious threat to human health if the groundwater aquifer is used as water supply or the reservoir is connected with water supplies.

Modelling CO_2 intrusion into groundwater aquifers revealed mobilisation of lead and arsenic as a result of the contamination, while for aquifers with low velocity, the impact of CO_2 intrusion can be more significant but is also more localised (Zheng *et al*., 2009).

Another aspect of CO_2 leakage into the groundwater is the interactions of co-injected/co-transported gases with the mineral matrix and the subsurface water. According to the modelling work of Harvey *et al*. (2012), there is a significant difference between the geochemical impact of a mixed gas (99.4% CO_2, 0.1% CO, 0.1% NO_x, 0.3% SO_x and 0.1% CH_4) and a CO_2-only stream (which cannot be obtained with the current capture technologies) as the co-injected/co-transported gases could potentially influence aqueous speciation and mobility of redox-sensitive elements such as Iron and Arsenic. Co-transported NO_x or SO_x into potable groundwater or soil pore water could contribute to additional lowering of the pH (up to 1 unit) that could lead to enhanced release of trace metals and formation of carcinogenic nitroso compounds (from Nitrogen dioxide NO_2 and organic matter) (Harvey *et al*., 2012). The same authors also proposed the conceptual framework for assessing geochemical impact of CO_2 on near surface environments, presented in the Fig. 3-2.

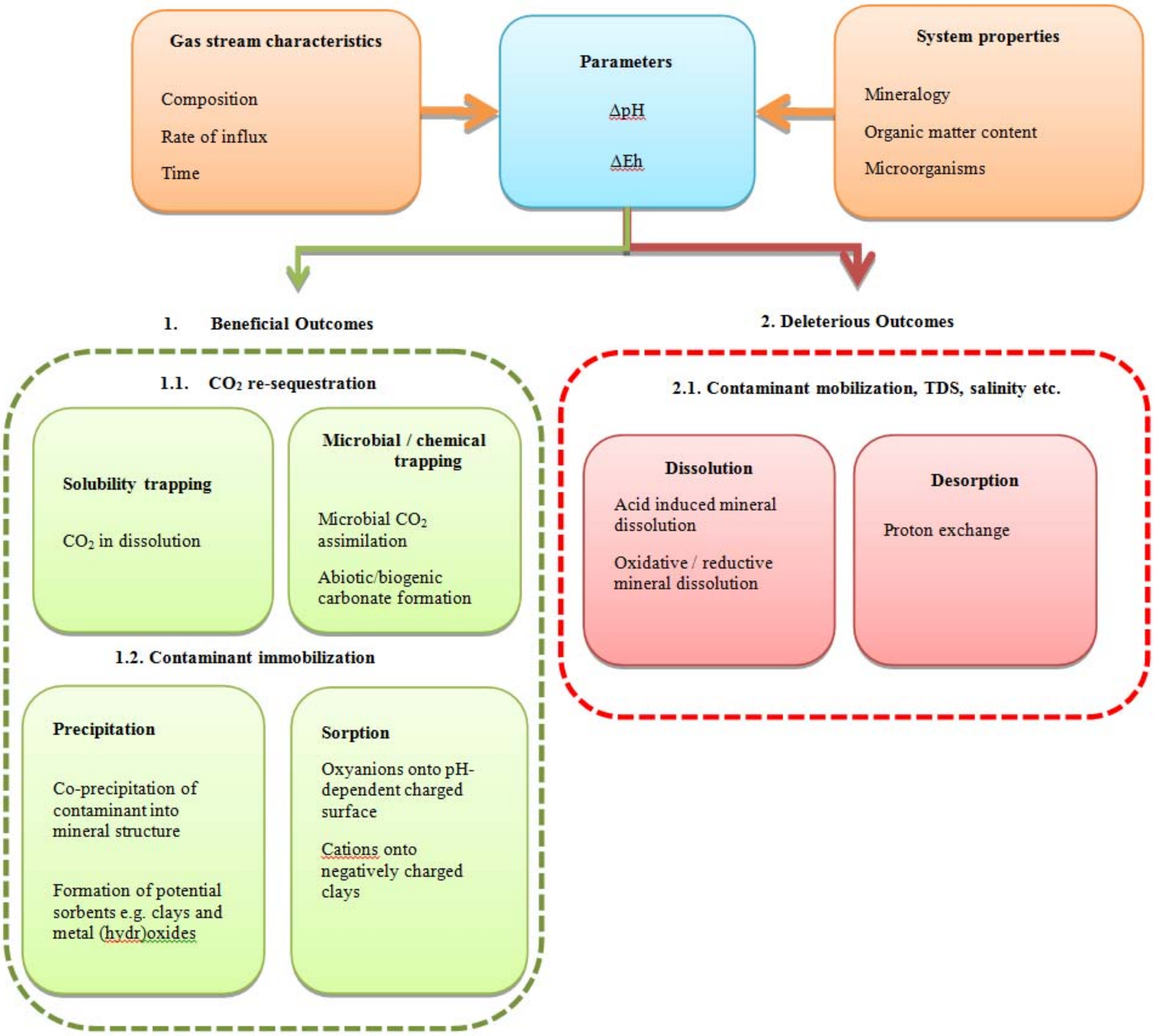

Fig. 3-2: A conceptual framework for assessing geochemical impact of CO2 on near surface environments (after Harvey *et al*., 2012)

3.4.2 Effects of leakage of CO_2 in the subsurface (soils)

The study of natural analogues for CO_2 leakage in the near surface (in soils) revealed that there is a strong negative correlation between O_2 and CO_2 contents. CO_2 progressively replaces O_2 and creates an almost anoxic environment (Gal *et al*., 2011). Therefore, the primary impacts of a CO_2 leakage in the near surface would be soil acidification and toxicity. This can furthermore lead to plant stress or death and disturbances of animal or microbial activity in the sub-surface. Although plants have a higher tolerance for CO_2 than animals, prolonged leaks could suppress respiration in the root zone (Damen *et al*., 2005). It is estimated that soil CO_2 levels above 10–20% inhibit root development and decrease water and nutrient uptake (IPCC, 2005). The degree of impact depends though very much on the sensitivity of species, the rate and geometry of leakage. Some species could adapt and recover in time or they could be more tolerant to soil chemistry changes (Kirk, 2011; Al-Traboulsi *et al*., 2012).

A complex two seasons study made at a naturally gas vent within Latera geothermal field emphasised the significant impact of CO_2 leakage in the soil. In the gas vent area (6 m diameter) the vegetation is absent (Fig. 3-3), pH is very low (3.5) and there are changes in mineralogy and bulk chemistry (Beaubien *et al*., 2008). In the area with a soil CO_2 concentration varying from 5 to 40 % at 10 cm depth, only grasses were found growing, demonstrating their increased tolerance for CO_2.

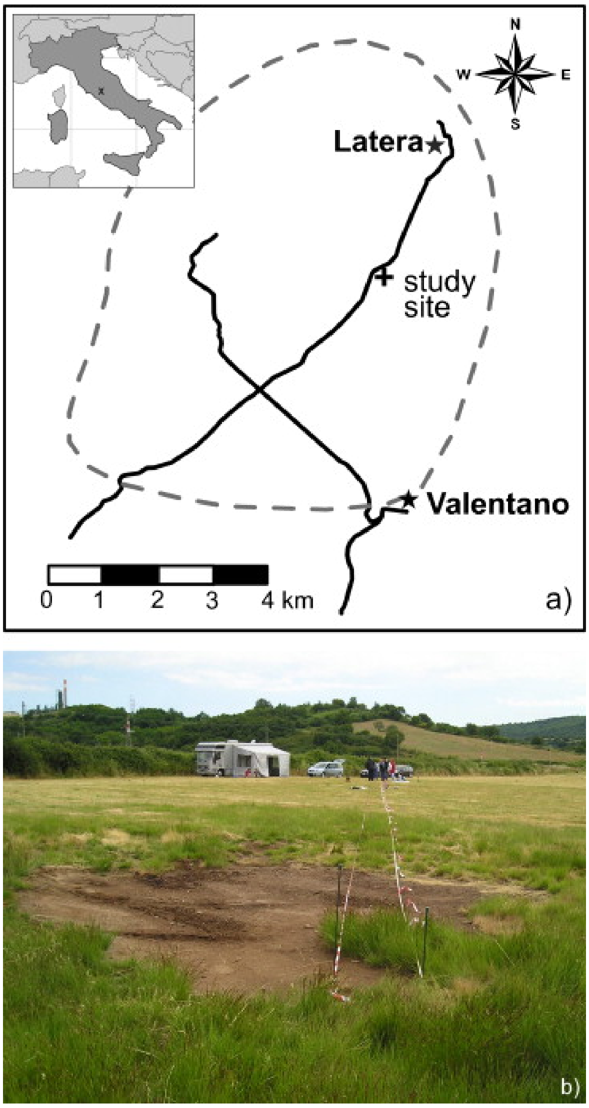

Fig. 3-3: Location map (a) and photograph of the studied gas vent (b) (Beaubien *et al*., 2008).

Approximately the same results for the botanical survey were found also at the Laacher See site (Germany) in 2008. Although dicotyledonous plants generally do not seem to tolerate high concentrations of CO_2 in soil, plants from this group (*Polygonatum arenastrum*) were observed at this site on transects where CO_2 concentration was 10-35% at 15 cm depth and 35-90 % at 60 cm depth and actually absent in areas of decreased CO_2 concentrations (Krüger *et al*., 2011). Therefore, Krüger *et al*. (2011) concluded that this plant could be used as a bio indicator for high CO_2 concentrations in soil at this particular site and that the botanical impact of CO_2 leakage is site specific and depends on factors as soil moisture and pH as well as plant species.

Another example of the botanical effects of the CO_2 leakage in the near surface is offered by the case of Mammoth Mountain, California, USA where a large area of coniferous forest was killed due to a diffuse magmatic CO_2 emissions (Farrar *et al*., 1999) that started prior to 1990 based on radiocarbon measurements of tree rings (Cook *et al*., 2001). The total amount of magmatic CO_2 emitted in 1996 was estimated to around 530 tonnes per day (Farrar *et al*., 1999). Soil gas readings showed CO_2 levels up to 95% in 1994 and levels of 15–90% in 2001 (IPCC, 2005). Average CO_2 flux rates in the affected areas were around 300 tonnes per day in 1996 (Cook *et al*., 2001) and 90–100 metric tonnes per day in 2001 (in the largest affected area, Horseshoe Lake) (IPCC, 2005). In addition to soil gas surveys, airborne remote sensing is also used to map tree health in this region.

A less studied effect of a CO_2 leakage in the near surface is the one associated with microorganisms. The survey made at a Laacher See vent in 2008 showed differences in the microbial activity and microorganism numbers on soil samples collected from CO_2 rich areas and control points with background CO_2 concentrations (Krüger *et al*., 2011). A decrease in the number of bacteria towards the centre of the vent and an increase of archaea number in the soils with higher CO_2 concentration was observed. The authors concluded that the rise of CO_2 concentration in soil led first to microaerobic and eventually to anaerobic conditions favouring the development of methane producing or sulphate reducing bacteria communities, thus the ecosystem adapted to CO_2 enrichment by substitution of species (Krüger *et al*., 2011).

3.4.3 Effects of leakage of CO_2 into the marine environment

Carbon dioxide leakage into the marine environment is a great threat for marine life and human health. The impact of the effects depend on the rate of leakage, extent and geometry of leakage, nature and composition of marine sediments, sensitivity of species to increased contents of CO_2 and the presence of other contaminants in the CO_2 stream.

One of the effects of an eventual leakage into the marine environment would be acidification of the oceans caused by a decrease in pH. A study made at a natural underwater gas vent near Panarea Island (Italy) in 2008 revealed that in the gas vent area the pH has decreased to 7.68 at 10 m depth and 7.78 at 5 m depth (see Fig. 3-4.) from the normal values of 8-8.2 (Espa *et al*., 2010).

Seawater acidification together with an increase of CO_2 content in marine sediments may produce adverse effects to marine life such as: dissolution of calcareous shells, decrease in ability to build calcareous skeletal structures including reefs, metabolic rate reduction, decrease in reproduction rates and increase of mortality rates, both among planktonic and benthic organisms (Kirk, 2010). The decrease of pH in marine sediments can also lead to the mobilisation of trace metals that can have direct toxic effects or can accumulate in the food chain (OSPAR, 2007). This may pose an indirect hazard for human health and life.

Moreover, the other contaminants that can be present in the CO_2 stream could increase the negative impact of a CO_2 leak, but this issue is not yet well understood and more research is required.

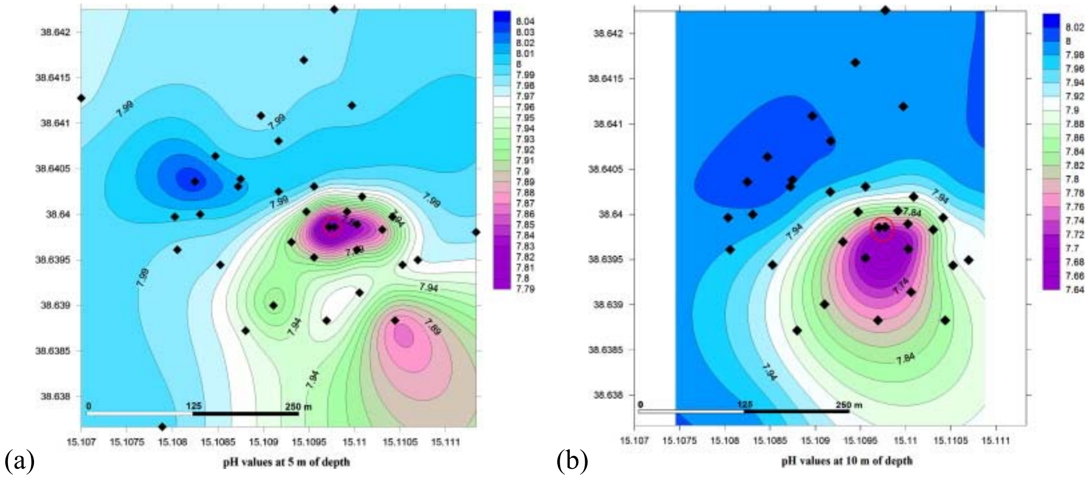

Fig. 3-4: pH values at 5 m depth (a) and 10 m depth (b) (Espa *et al*., 2010).

The ability of the marine ecosystem to recover after a leakage has been stopped is an issue that needs more research and can only be fully assessed on a site-specific basis. It is thought though that shallow ecosystems recover faster than deep ecosystems (OSPAR, 2007).

3.4.4 Effects of leakage of CO_2 at the surface and in the atmosphere

Leakage of CO_2 from the ground into the atmosphere (also referred to as “seepage”) can result in health, safety, and environmental risks, including asphyxiation of humans or animals. It is well known that high concentrations of CO_2 are toxic to most air-breathing animals, including humans. The effects of CO_2 depend though on the concentration of CO_2, the duration of exposure and the concentration of O_2 (Rice, 2004). According to the same author the clinical effects of the CO_2 exposure over the human health are physiological (e.g. increase of the respiratory rate, cardiac arrhythmias), anaesthetic (depression of the central neural system activity) and lethal (severe acidosis and anoxia). CO_2 can also act as an asphyxiant by displacing atmospheric O_2. Signs of asphyxia are noted when the atmospheric oxygen concentration is ≤ 16% and it is fatal at ≤ 8% (Rice, 2004). This preliminary evaluation suggested that acute exposure to CO_2 concentrations <3% and prolonged exposure to concentrations around 1% may significantly affect health in the general population. Besides the duration and magnitude of exposure, the effects of CO_2 exposure depend also on individual factors, such as age, health, physiologic make-up, physical activity, occupation, and lifestyle (Rice, 2004). Several categories of sensitive population groups identified in the same study include cerebral disease and trauma patients, infants and children, individuals performing complex tasks, medicated patients, panic disorder patients and pulmonary and coronary disease patients.

Although it cannot be considered as analogues for eventual CO_2 leakage from a storage site, as the release of CO_2 was much more rapid than would be expected from a storage site, the disasters from lake Monoun (1984, 37 humans died) and lake Nyos (1986, 1,700 people and 3,500 livestock killed) from Cameroon emphasise the potential impact that a sudden and large-scale release of CO_2 can have on human population. At each of these deep crater lakes, CO_2 had been accumulating at the deep lake waters and which was suddenly released. The release was suddenly triggered by a sudden event (landslide according to one theory). Being denser than air, the CO_2 cloud remained for a relatively long period near the ground in the valley. At Lake Nyos the CO_2 cloud resulted in more casualties as the released quantity was very large (up to 300 kt) and extended over 25 km from the lake, affecting several villages. The topography of the Lake Nyos area also played in crucial role in the disaster since it did not allow the cloud to disperse (Damen *et al*., 2005). In typical topographical conditions and at normal wind velocities, small, isolated leaks will be dispersed. These cases highlight the need for paying special attention to monitoring the areas around the storage site that offer good conditions for the accumulation of large quantities of CO_2 if released from the storage site. It is also worth mentioning that, according to modelling results, a CO_2 leakage from a storage site, even from a well, will be at a much slower rate than the leak at the so called "killer lakes" such as Lake Nyos.

3.5 Occupational guidelines regulating CO_2 levels in the environment

Currently there are no general guidelines or regulations for CO_2 levels in the environment. The only guidelines are the occupational ones, presented in Tab. 3-2.

The effects of CO_2 exposure on animals are similar with those associated with humans.

Tab. 3-2: Occupational guidelines for CO_2 (from the Guidelines for volcanic gases and aerosols, IVHHN, 2013).

Country/ Institution	Level %	Level mg m^{-3}	Averaging Period	Guideline Type	Date of Implementation	Relevant Law	Notes	Ref.
EU	0.5	9,000	8 hour TWA	OEL		Commission Directive 91/322		EU, 2013
UK	1.5	274,000	15 min	MEL		ILV		HSE, 2002
	0.5	9,150	8 hour TWA	MEL		ILV		HSE, 2002
USA	3	540,000	15 min	STEL	2003	NIOSH		NIOSH, 2013
	>0.5	9,000	8 hour TWA	PEL		OSHA Regulations (Standards - 29 CFR)	1	OSHA, 2013
	0.5	9,000	10 hour TWA	REL	2003	NIOSH		NIOSH, 2013

[1] ppm by volume at 25ºC and 760 torr

Another ill effect of potential CO_2 leakage into the atmosphere from storage sites is linked to the failure to reduce CO_2 emissions and the climate change effects that CO_2 capture and storage is designed to reduce. Leakage of CO_2 into the atmosphere could mean that emission targets may not be reached and additionally, the emitted CO_2 would have to be accounted for (by compensation) through the EU ETS.

3.6 Conclusions

The main purpose of CCS technology is to prevent any further emissions of CO_2 to the atmosphere from fossil fuel based energy production and other industrial processes which produce CO_2. Leakage prevention is therefore essential in order to fulfil the purpose of the technology, in addition to avoiding any of the known negative effects to the environment and human health. It is therefore of exceptional importance that all risks relating to leakage of CO_2 are considered and accounted for during a storage project, starting at the very beginning, during the site selection stage. Leakage of CO_2 at a storage site could occur from the storage reservoir through migration pathways that pass through the overlying bedrock to the surface. These pathways may be natural (e.g. fractures) or anthropogenic (e.g. wells or mining infrastructure). Anthropogenic pathways such as artificial fractures created through hydraulic fracturing during the extraction of minerals and hydrocarbons may be a potential interest of conflict with geological storage of CO_2 where they affect cap rock properties.

Regulatory regimes like OSPAR and the EU CCS Directive clearly state the importance of risk analysis and risk management during a storage project in order to decrease the risk of leakage and therefore its effects on human health and the environment. Since the geological conditions of each potential storage site are site-specific, the laws and international agreements have to take this into account. The characterisation of the storage complex and monitoring the behaviour of the injected CO_2 are two mandatory operations in a CO_2 storage project and are regulated both by OSPAR and the EU CCS Directive. Together they require accumulation of knowledge that can be used to detect leakage from the storage site and enable the appropriate remediation measures to be undertaken in order to prevent leakage or to decrease the effects of leakage.

The composition of the CO_2 stream is also regulated. The composition of the CO_2 stream will determine the effects of leakage from a storage site since the expected chemical and physical reactions within a storage site are dependent on the composition of the injected CO_2 stream and the properties of the hosting rock. The effects of impurities in the CO_2 stream on potential leakage pathways are yet not fully understood and the risk of enhancing or causing leakage pathways is most likely dependent on the composition of the injected CO_2 stream and the surrounding bedrock.

Local laws and regulations will affect activities at and requirements for the storage site. The EU CCS Directive is transposed by the member states with some slight variations in detail (where it has been fully implemented). Other local planning, health and safety and environmental laws and regulations will also affect the storage site activities. In addition, conflicts of interest and their consequences should always be considered in terms of the physical planning and regulatory regimes of each country.

4 DIRECTIVES AND REGULATIONS RELATED TO STORAGE SITE MONITORING

This chapter provides an overview of how monitoring is addressed in legislation and directives, how guidelines and protocols have been developed to interpret the legislation and how some of the early integrated industrial scale CCS projects have incorporated monitoring plans in their permit applications.

The chapter starts with a thorough review of the various legislative regimes, with a main focus on Europe and the CCS directive. The associated guidelines developed in the so-called Guidance Documents provide more practical information on how to translate legislative monitoring requirements to a practical implementation. Besides the CCS directive, the ETS directive and its associated ETS-MRG guidelines are discussed. The latter describe at a high level, how monitoring should be measured and quantified in case leakage to the surface or sea water column occurs.

Besides European legislation, developments in the US, Canada and Australia are described, where legislation is furthest advanced after Europe. It is not surprising, that many similarities can be observed.

Finally the contents concerning monitoring of various international documents such as OSPAR, the London Convention, the IEA-MRF and CO2QUALSTORE are described. It must be noted, that the high level content of most of these documents have been incorporated in the EU storage directive.

The last part of the chapter is dedicated to examples of integrated industrial scale projects implementing monitoring plans in their permit applications (several located in the EU and one in Canada). Information has been taken from published FEED studies as well as from storage permit applications. As one might expect, major differences exist between onshore storage (e.g. the Quest project in Canada) and offshore storage (e.g. the ROAD project in the Netherlands). However, it is worth mentioning, that with existing current technology decent monitoring programs have been proposed.

Risk assessment is considered a key element in a CO_2 storage project, as exemplified by the prominent position of risk assessment in the various regulatory documents including the EU storage directive. The most important tool for successful risk management is monitoring. Smith *et al*., 2011a provide a good basic definition of monitoring, namely “continuous or repeated observation of a situation to detect changes that may occur over time”. The essential role of monitoring according to the EU directive Guidance Document 2 can be summarised as: a) to confirm containment of CO_2, b) to alert in case of increased leakage risk, c) to identify leakage and/or significant irregularities, and d) to verify the CO_2 plume behaviour. Moreover, monitoring should ensure the effectiveness of any corrective measures applied. As a result, monitoring issues are given top priority in the EU and other international legal documents and guidelines.

The regulatory process on CCS started in the early nineties after energy policy strategies were adopted at an international level. The list of regulatory documents which paved the way towards CCS at the industrial level is extensive. The aim of this Chapter is not to describe all of these documents in detail, but rather to point to some of the most prominent milestones for the implementation of CCS technology with a particular focus on monitoring and reporting with respect to the geological storage of CO_2 at the EU level.

At present, the EU legal framework that enables CCS industrial operations is in place, though revisions based on experiences are still foreseen by June 30, 2015 (recital 48, EU CCS Directive 2009/31/EC).

Regulatory processes ran simultaneously in other parts of the world. Relevant legislation on monitoring and reporting for CCS is currently implemented amongst others in the USA, Canada and Australia.

In this Chapter specific provisions and solutions related to monitoring and reporting issues from different regulatory regimes are compared, but with the main emphasis on EU regulations. The following sections discuss various approaches that were followed in individual countries, differences and similarities in provisions applied, specific requirements in the reporting and verification process and solutions adopted for on- and offshore storage sites.

The main emphasis is on the EU CCS Directive, but a brief overview of other documents will be discussed. In general one could say that all early regulatory documents are included in the EU CCS Directive.

As examples the monitoring plans of a number of industrial projects, that will operate under the umbrella of the most recent CCS legislation, have been analysed. It must be noted, that none of these projects is operational yet, and the advancement in applying for storage licenses varies widely. Nevertheless, it is instructive to see, how legislation has been interpreted and applied by the various industrial proposers in their applications. The analysis is limited in the sense, that it is only based on information publicly available. A number of potential storage sites in Europe have been analysed, of which the information on one Dutch and two UK projects is furthest advanced. Besides the European sites, also the Quest project in Canada has been analysed, since it received a license with minister's approval together with well license approval in 2012.

4.1 Regulations concerning monitoring

4.1.1 Regulations in Europe

The fundamental legal EU document is the Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006 (the so called CCS Directive). This is a legally binding document for all EU Member States. The deadline for the transposition of this Directive into national laws, regulations and administrative provisions of the Member States was 25 June, 2011. Currently, the process is progressing, but still ongoing. In order to assist potential stakeholders and to ensure consistent implementation of the CCS Directive throughout the EU, the European Commission issued a set of four Guidance Documents (CE, 2011a ,b, c and d), which are legally non-binding documents. Guidance Document 2 (EC, 2011b) is specifically devoted to characterisation of the storage complex, CO_2 stream composition, monitoring and corrective measures and shall be discussed in further detail later in this Chapter.

The recitals to the EU CCS Directive include some specific statements related to monitoring and reporting. First of all, the need to establish a regulatory framework is recognized in Recital 7: The framework should be based on an integrated risk assessment for CO_2 leakage that should consider requirements for site selection, monitoring including reporting, and remediation measures to be applied should any damage occur.

Recital 28 stresses the importance of monitoring in assessing deviations from expected behaviour of the injected CO_2, detecting (unexpected) migration or leakage, and finally assessing the impact of leakage on the environment and/or human health. The Member States (more specifically the competent authorities) are required to ensure that the operator monitors the entire storage complex and the injection facilities according to the specifically designed and approved monitoring plan during the pre-injection phase, during injection operations and during the post-closure phase. Interestingly, this article puts geological storage under the seabed in a particular position, for which adapted monitoring procedures are foreseen, as if onshore CO_2 storage is the norm.

The EU CCS Directive is also very explicit in terms of liability (for environmental damages, for climate damages). Depending on the type of damages, other related EU regulations come in play, as described in Recital 30.

Monitoring requirements after a storage site has been closed and after the transfer of responsibilities from operator to the competent authority consist for an operator of providing a financial security at the moment before transfer of responsibility, that covers at least anticipated monitoring costs for a period of 30 years (Recital 37). Individual member states can decide to deviate from this 30 years period. This demand is not very clear yet, and should be based on guidelines, that are not explicit though. Currently the amount of financial security demanded is difficult to predict, particularly since it may also cover contingency costs.

Monitoring is further mentioned and specified in Article 13 and Annex II of the CCS Directive. In the following text this will be elaborated together with the more detailed description as provided in Guidance Document 2 (EU, 2011b).

According to Guidance Document 2, the principal objectives of monitoring are a) to confirm containment of CO_2, b) to alert in case of increased leakage risk, c) to identify leakage and/or significant irregularities, and d) to verify the CO_2 plume behaviour. Monitoring should be performed already during the project development and then run during the operational phase, and in the post-closure phase. According to the CCS Directive the operator of the storage site is liable for monitoring and reporting from the beginning of storing activities to the moment of transfer of responsibilities from the operator to the competent authority. Article 13 of the EU CCS Directive precisely defines what needs to be monitored (i.e. generally three basic units: injection facilities, the storage complex including the CO_2 plume when possible and the surrounding environment where appropriate). The operator must obtain the Storage Permit before the start of any injection activities. An initial monitoring plan is the obligatory constituent of the Storage Permit. It should be based on the risk assessment and the site characterisation provided within the CO_2 Storage life cycle risk management framework (Guidance Document 1, EU, 2011a). Here, monitoring requirements are defined and threshold values for specific parameters may be applied for preventive and corrective measures. Updates of the monitoring plan are required on a regular basis at least every five years. They should take into account new knowledge and best available technology at the time of the design. It is crucial to follow the behaviour of the storage complex and of the adjacent environment in order to evaluate its compliance with the predicted dynamic simulations. As long as the predicted models agree with the observed data (i.e. the storage complex behaves as expected), the monitoring can be considered as sufficient. If significant deviations from the expected behaviour are observed, the models should be re-calibrated and/or updates in the monitoring plan should follow and/or preventive and corrective measures should be imposed. The monitoring plan (and also corrective measures plan in case of leakage or significant irregularities) should be agreed and approved by the competent authority. Identification of preventive measures should be included in the Storage Permit application. Preventive and corrective measures are imperative in the EU CCS Directive. It is one of the monitoring aims to trigger early warning in case of any leakages and/or significant irregularities. Implementation of preventive measures is aimed at preventing irregularities to occur. It is explicitly required that the monitoring plan and the corrective measures plan are prepared hand in hand and are delivered at the time of the storage permitting procedure. Moreover, the operator should describe adequate preventive and corrective measures. It should also be possible to assess the effectiveness of corrective measures. Competent authorities may require additional corrective measures to be taken by the operator at any time.

The intensity and performance of monitoring are site specific and shall depend on risk assessment analysis. Higher degree of monitoring activities may be appropriate in the initial stages of storage site operations. After the transfer of responsibilities the intensity of monitoring may be reduced, but only to the degree which would ensure adequate detection of leakage or any significant irregularities.

The set-up of optimal monitoring methodologies will be strongly site-specific and risk based. The EU CCS Directive specifically requires to "be based on the best practice available at the time of the design", but it is not prescriptive in which measuring methods or technologies should be used. The appropriate monitoring options to be considered include (Annex II, EU CCS Directive):

- Technologies that can detect the presence, location and migration paths of CO_2 in the subsurface and at the surface;
- Technologies that provide information about pressure-volume behaviour and areal/vertical distribution of the CO_2 plume to refine numerical 3D simulation to the 3D geological models of the storage formation;
- Technologies that can provide a wide spatial spread in order to capture information on any previously undetected potential leakage pathways across the areal dimensions of the complete storage complex and beyond, in the event of significant irregularities or migration of CO_2 out of the storage complex.

The requirements for monitoring methodologies anticipate application of direct or indirect methods, static and dynamic modelling and spatial and temporal coverage.

Apart from the risk based monitoring plan, the EU CCS Directive explicitly defines a number of mandatory parameters to be monitored in all cases (Annex II, EU CCS Directive):

- Fugitive emissions of CO_2 at the injection facility;
- CO_2 volumetric flow at injection wellheads;
- CO_2 pressure and temperature at injection wellheads (to determine mass flow);
- Chemical analysis of the injected material;
- Reservoir temperature and pressure (to determine CO_2 phase behaviour and state).

As mentioned earlier, the optimal monitoring plan should be site-specific and risk-based and the CCS Directive is therefore not very prescriptive in terms of measurement methods or technologies to be applied, acknowledging the wide range of geological settings, site conditions and storage options across Europe. According to Guidance Document 2, about 60 different methods have been identified to be potentially appropriate for monitoring (reviews performed by IPCC, IEA, ASPEN, NSBTF, the IEA GHG Report 2012/02 and Rütters *et al.*, 2013). Guidance Document 2 proposes elements for monitoring to be considered (such as operational, plume, pathways, environment-leakage) and suggests suitable methods and techniques to be applied (see Fig. 4-1).

Regardless of the method, it is necessary to consider potential limitations of individual methods (i.e. detection limits, accuracy, resolution, applicability to the specific environment, frequency of measurements as well as costs). Because of these, an integrated monitoring approach is required.

Performance Standards and Key Performance Indicators can be introduced for monitoring to fulfil its objectives. Performance Standards should address the following issues: what to monitor, when and how often, accuracy of measurements, what are key monitoring parameters and their threshold values, establishing baseline for background emissions etc.

The monitoring plans must contain information which parameters are to be monitored, monitoring technology together with the justification for the technology choice, spatial and temporal coverage of monitoring as well as all mandatory parameters defined in Annex II (see earlier in this Chapter). If necessary, required monitoring and optional monitoring should be applied. GD 2 proposes a template for a monitoring plan (Tab. 4-1) in which the requirements pursuant EU CCS Directive are reflected. Moreover, the operator is required to present a portfolio of monitoring methods which are appropriate according to identified risks at individual location.

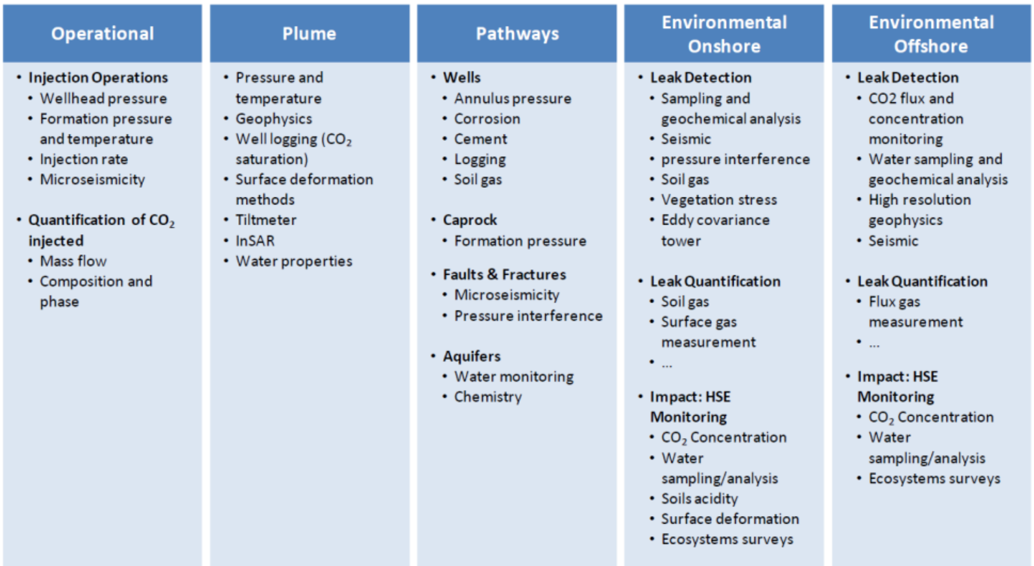

Fig. 4-1: Different methods and techniques suitable for monitoring (Guidance Document 2, EC, 2011b).

Tab. 4-1: Proposed format of monitoring plan template with example information (Guidance Document 2, EU, 2011b).

Parameter to be monitored*	Technique adopted	Category of monitoring			Project phase and frequency				Location	Normal situation		Alert value		Contingency value (significant irregularity)	
		Mandatory	Required	Contingency	Pre-inj	Inj	Post-inj	Long-term stewardship		Expectation value	Accuracy	> Threshold 1	Action**	> Threshold 2	Continger measure
Injection rate	Flow meter	x				Cont			Well head						
Pressure	pressure device	x			Baseline data	Cont	Cont	Every year	Well head + Down hole			Larger than hydrostatic pressure	Microseismic monitoring of seal	Larger than fraccing pressure	Stop injec
Temperature	thermometer	x			Baseline data	Cont	Cont	Every year	Well head + Down hole						
Injected gas composition	Gas samples	x				Cont			Well head	Defined %		Allowed fluctuations	Adapt gas composition, reduce injection rate	Above allowed fluctuations	Adapt ga composit stop injec temporar
Fault integrity	Repeated 3D seismic		x		Baseline survey	Order of years, based on modelling	Possible survey after several years	Possible survey after several years	Fault area	No signal changes		Signal change in the seal		Signal change above seal	
	Aqueous chemistry (CO2, pH)		x			roughly yearly									
Well integrity	Annular pressure		x			order of few months			Well bore	t.b.d.		t.b.d.		t.b.d.	
	Wireline Logging		x			order of few months			Well bore	t.b.d.		t.b.d.		t.b.d.	
	Optical Well Logging		x			order of few months			Well bore	t.b.d.		t.b.d.		t.b.d.	
	Cement Bond Logging		x			order of few months			Well bore	t.b.d.		t.b.d.		t.b.d.	Cement
Microseismic monitoring	Geophones behind the casing of a well			x	Baseline data	Cont	(Cont)		Injection well	No events in caprock		Events in the caprock		Large events in the caprock	Stop inje

*Follows from the risk assessment
** t.b.d. by operator examples are updating model additional monitoring
*** t.b.d. by operator, examples are stop injection, back-production, well workover, contingency monitoring
Note: This table is not intended to represent a full monitoring plan, but to show example information to illustrate how the table should function. The numbers and data do not represent real site-specific values.

Monitoring results and all information arising from monitoring should be regularly reported to the competent authority. The frequency should be at least once a year until the transfer of responsibilities. Obligatory elements to be reported include all monitoring results, monitoring technology deployed, the quantities and properties of the injected CO_2 stream, proof for providing financial security (Guidance Document 4) and any other information the competent authority considers necessary to assess compliance with the Storage Permit. Monitoring results shall be presented, interpreted and compared with the predicted models. If significant deviation between the observed and predicted values is identified, recalibration of models should follow and the monitoring plan updates are to be developed. In addition, any significant irregularity must be immediately reported to the competent authority. Data retention and data ownership are also addressed in Guidance Document 2.

Reporting requirements as well as approval procedures of the monitoring plan differ under the CCS Directive and under the EU ETS Directive. As a consequence, close communication of both competent authorities (in case not the same) is required since parts of the documentation overlap. Tab. 4-2 shows the reporting requirements under the two Directives. In Annex V of the EU ETS Directive (2003/87/EC), the methodology for verification is defined. This should include strategic analysis, process analysis and risk analysis, followed by the preparation of the validation report. Minimum competency requirements for the verifier are also stated. Evaluation of performance includes a comparison of the predicted and actually observed data. Under the EU CCS Directive the focus is on safety and environment and under the EU ETS Directive the focus is on effectiveness in emission reduction.

Tab. 4-2: Comparison of Reporting Requirements (Guidance Document 2, EU 2011b).

Reporting Requirement	CCS Directive	ETS MRG*
Mass of CO_2 injected during the reporting year	Yes	No
Mass of CO_2 stored during the reporting year	No	No
Cumulative mass of CO_2 stored at the site	Implicit	No
Characterisation of the CO_2 stream (including composition)	Yes	Yes
Monitoring results	Yes	Yes
Characterisation of the proposed storage-site(s)	No	Implicit
Potential leakage pathways	Implicit	No
Source of CO_2 injected and infrastructure used	No	Yes
Leakage	Implicit	Yes
Corrective measures taken	Implicit	Implicit
Modelling updates	Yes	Yes
Fugitive emissions from storage site	Yes	Yes
Third party verification	No	Yes
Environmental impacts (potential)	No	No
Environmental impacts (actual)	Yes	No
Environmental impacts (from potential leakage)	No	No
Environmental impacts (from actual leakage)	Yes	No
Permits issued	No	Yes
Guidelines	No	Yes

* Based on (1) the Commission Decision 2010/345/EC amending Decision 2007/589/EC as regards the inclusion of monitoring and reporting guidelines for greenhouse gas emissions from the capture, transport and geological storage of carbon dioxide, and (2) Commission Decision (2007/589/EC)

Monitoring reports need to be reviewed and approved. Moreover, inspections are also required. Routine and non-routine inspections could be in a form of site visits and/or the verification of records. The timings for routine inspections are defined, but frequency may vary according to the site performance history.

In Articles 19 and 20 the EU CCS Directive envisages that Member States establish an effective system for financial security. This involves the operator's obligation to ensure adequate financial resources for all obligations arising from the permit. It is up to Member States to decide which financial security instruments or their acceptable equivalents would be directed and how to define the amount of the financial contribution to be made available by the operator. The proofs for financial security should be an integer part of the application for Storage Permit. The Guidance Document 4 (EU, 2011d) describes criteria and principles for financial security and recommends the established and low risk options. Guidance Document 4 also describes options for determining the amount of the financial contribution. The list of obligations which must be covered by financial security instruments explicitly includes monitoring, updates of the monitoring plan, and the required reporting of monitoring results in operational as well as in the closure and post-closure period (Guidance Document 4, EU, 2011d). In the event of changes to the assessed risk of leakage, updates of the financial contributions may be made.

It is important to also introduce another document EU CCS Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 that establish a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC (the so-called EU ETS Directive). Monitoring and Reporting Guidelines (MRG) (Commission Decision 2007/589/EC and its amendment Commission Decision 2010/345/EU) were issued to the EU ETS Directive. MGR describes how CO_2 emissions from storage activities should be accounted and reported to comply with EU ETS. During injection and storage operations, potential sources can arise from the fuel use at the injection site, from vented and fugitive emissions at the injection site and/or enhanced hydrocarbon recovery (EOR, EGR) procedures, and from leaking from the storage complex. The term “leakage” is precisely defined in the EU CCS Directive. As soon as a leakage is identified under the EU CCS Directive, the provisions from the EU ETS Directive MRG are triggered and quantification of CO_2 releases into the air or into the water column is required. Such leakage is considered as a new emission source and is characterised as climate damage. The new source exclusion is previewed only after successful application of corrective measures and after the moment the emission is not detected any longer. Some monitoring methods have the potential for the quantification of the emissions resulting from leakage and can therefore accommodate the requirements of both Directives. If necessary, monitoring previewed under the EU CCS Directive should be intensified in order to meet requirements of the EU ETS Directive. The integration of the provisions of the EU CCS Directive and the EU ETS Directive with respect to monitoring is necessary in order to ensure the compliance of both documents. The coherence of the EU CCS and ETS Directives is also relevant in reporting and verification procedures.

In summary, the EU CCS Directive and the EU ETS Directive (and its MRG) form the constituent EU regulatory framework regarding CCS. However, other legal and regulatory documents have also influenced the two directives, the most important being IPCC Special Report on CCS (2005) and the IPCC Guidelines (2006) and provisions from the OSPAR Convention (OSPAR, 2006).

4.1.2 Regulations in the US

The US geological storage legal and regulatory framework is based on the Safe Drinking Water Act from 1974, in which the US Environmental Protection Agency (EPA) is given the jurisdiction to regulate underground injection of any substances and thus protecting underground sources of drinking water from contamination.

In 1980, EPA issued the Underground Injection Control (UIC) programme. This distinguishes several classes of injection wells, e.g. Class II being relevant for EOR operations and Class V for experimental injections. It is worth mentioning here that the existing federal and state legal regimes developed for the EOR operations address many aspects of the requirements of geological storage, especially if the early phase of CCS implementation is performed within EOR operations. In December 2010, EPA adopted the rules for regulations of CO_2 injection wells for permanent underground storage of CO_2 within the UIC programme (USEPA, 2010a) by introducing a new Class VI.

In the USA, clarification of property rights which includes access to pore space was also a prerequisite legal issue in the implementation of commercial underground storage projects. The EPA Resource Conservation and Recovery Act (RCRA) (USEPA, 2011) exempts CO_2 stored underground as part of CCS operations from hazardous waste regulations (Pollak, 2012).

EPA UIC rules cover all phases from pre-injection to post injection site care. In order to support owners and operators of Class VI injection wells and the UIC Program permitting authorities, EPA issued a Guidance manual (EPA, 2013) which is just one of the series of technical Guidance Documents that EPA has developed. The requirements for Class VI refer to site characterization, modelling of the injected area, well construction and operations, monitoring of the CO_2 stream, financial responsibility, and periodic re-evaluation of the area and the updates of the project plan. Owners or operators are required to test and monitor the elements according to a Testing and Monitoring Plan submitted with a Class VI permit application and implemented throughout the storage operation and beyond. The Testing and Monitoring Plan must describe planned injectate monitoring, corrosion monitoring, pressure fall-off testing, ground water quality monitoring, CO_2 plume and pressure front tracking, and (if required) surface air and/or soil gas monitoring. The monitoring of mechanical integrity of injection wells is required. A set of available methods for internal and external mechanical integrity testing exist. In the operational phase, analysis of CO_2 stream and continuous monitoring of injection rate, pressure and volume, corrosion monitoring and pressure fall-off testing are required. Geochemical monitoring of ground water quality above the confining zone is required by using appropriate sampling techniques and sampling frequencies. Available methods for plume and pressure-front tracking include in-situ fluid pressure monitoring, indirect geophysical monitoring, ground water geochemical monitoring combined with computational modelling. The suite of testing and monitoring methodologies used shall be site specific, complementary; the monitoring frequency shall differ according to specific site conditions. If applicable, and if required by the UIC Program Director, the surface should be monitored as well.

Monitoring is required to be extended in the post-injection phase. The monitoring actions should define the area of review and should form an integer part of corrective action plans, testing and monitoring plans, injection well abandonment plans, post-injection site closure plans, emergency and remedial response plans. (USEPA, 2010a; Baker and McKenzie, 2011). The application document shall enclose all basic information of the site (maps, models, plans, designs, injection well construction etc.). Guidance to the EPA rules (USEPA, 2013) recommends a format and required reporting frequency of collected data and interpretation and the type of information and data that should be included. EPA serves as a permitting agency, but States may administer the UIC programme themselves, subject to the EPA approval.

Apart from the federal regulation framework, the States (about a dozen at a time) are developing their own frameworks to address geological storage. Dedicated legislation at the state level treats CO_2 as a valuable commodity rather than waste (as is the case for the EU). Some States provide for site review and permitting rules, monitoring and testing, site closure and post-closure rules. Transfer of liability and stewardship to government is foreseen.

Several sources notify there are still remaining uncertainties in the regulatory and legal frameworks for CO_2 storage. Consistent requirements will therefore be needed for monitoring, verifying, and reporting injected CO_2, and releases, if any. Liability issues will need to be clarified. In 2010, the EPA finalized its Mandatory Reporting of Greenhouse Gases from Carbon Dioxide Injection and Geologic Sequestration (Reporting Rule - Subparts RR for CO_2 geological storage facilities and Subpart UU that conduct all other CO_2 injections) (Baker and McKenzie, 2011). Facilities covered by Subpart RR must monitor and report CO_2 received, injected, produced, emitted from surface leakage and equipment leaks and CO_2 sequestered in subsurface geologic formations. They must also submit a Monitoring, Reporting and Verification plan (which is to include leakage risk assessment, monitoring strategy and pre-injection baselines) for EPA approval. Facilities covered by Subpart UU have a lesser reporting requirements. These facilities must report the source of the CO_2 and mass of CO_2 received.

Greenhouse gas reduction targets have still not been adopted at the federal level. However, numerous States have accepted greenhouse gas limitations and adopted binding documents. Because of these facts, in the USA the driver for CCS deployment is EOR, not policy or emission reduction. According to some sources (Hunton and Williams, 2012), industry has expressed concerns the Class VI requirements are too stringent and may impede geologic sequestration. It is noted that CO_2 used for enhanced oil recovery is a subject to less restrictive standards (Class II). It may appear necessary to develop a transitional regulatory framework for shifting from EOR operations (incidental injections) to CCS operations (incremental injections). Financial security aspects for a post-injection period would also need to be assured and regulated.

4.1.3 Comparison between regulations in the US and in the EU

The World Resources Institute (WRI) developed a dynamic web-based tool that allows visitors to compare CCS regulations and regulatory proposals across a number of key issues. The tool compares CCS-specific regulations from EU (the EU CCS Directive), USA (the USEPA rules) and IEA Model Framework (IEA MRF) to each other to convey where key issues are managed similarly or differently and where they are not addressed. Based on this tool, major differences between the USEPA rules and the EU CCS Directive were found (WRI based tool):

- Both regulations set monitoring durations (EPA 50 years and EU 20 years, but both are flexible in this respect) and anticipate to be decreased if evidence exist the storage project will not leak. However, the CCS Directive applies stricter performance-based standards requiring that all available evidence indicates that the stored CO_2 will be completely and permanently contained.
- Major differences exist on the storage site registration: the EU CCS Directive specifically mentions that a publicly accessible registry should be created and maintained, while EPA does not specify anything like it.
- In terms of financial responsibility both require that the operator demonstrate financial responsibility for the expected costs of a storage project. However, the EU CCS Directive includes coverage for 30 years of monitoring as part of the plan; under the EPA rule the default time period would be 50 years, although this is not mentioned explicitly. In addition, the EPA addresses neither the funding for long-term stewardship nor the transfer of responsibility of the site to a long-term caretaker. Both regulations anticipate funding security.
- EPA does not prescribe a mechanism for long-term stewardship after a site is closed, while the CCS Directive requires the transfer of responsibility for a closed site to a competent authority.
- Major differences exist in terms of post-closure definition. EPA defines it as a period of time after injection, but before the site is closed, during which the operator is responsible for monitoring and verification. However, the CCS Directive defines post-closure as the time after the site is closed, including before and after responsibility of the site is transferred.
- Injection pressure determination is also dissimilar: EPA states that operators cannot exceed 90% of the fracture pressure while the EU CCS Directive does not impose specific restrictions – the key question is whether the available storage space would be significantly decreased by and whether certain cap rocks would fail at an injection pressure greater than 90% of the fracture pressure.
- Both rules include consideration about the area of elevated pressure as part of the project footprint that is monitored. EPA rules are much more definitive and specifically demand testing and monitoring. However, the EU CCS Directive does not explicitly mention an area of elevated

pressure, but instead more generally focuses on monitoring "pressure-volume behaviour and areal/vertical distribution of CO_2-plume."

- Both preview the model updates and include provisions for using a predictive model that is based on operational data, which is updated throughout the project. The detailed provisions on the model updates differ slightly as the EPA's regulation requires updates also after a fixed period of time (every five years and when the area of review is updated).
- Mixed approaches about monitoring requirements exist. Both frameworks identify data requirements for operational monitoring that are largely consistent and both recommend that the operator report the composition of the injected fluid, the volume injected, the flow rate, and reservoir pressure. Meanwhile, the EU CCS Directive focuses on the outcomes rather than on specifying methods. Moreover, the EPA rule does not specify reporting leakage emissions as an operational data requirement.

As concerns flexibility of monitoring area, choice of monitoring tools and sitting requirements focused on geological characteristics, both regulations are comparable.

4.1.4 Regulations in Canada

Canada shares jurisdictional responsibilities between federal and provincial jurisdiction. Issues that concern environmental protection fall under both regulatory authorities. Various constituents of the CCS chain thus fall under both regulations. However, storage issues are subject to provincial competency. Four provinces are currently proceeding with CCS regulations: Alberta, Saskatchewan, British Columbia and Nova Scotia. Their CCS regulations are currently in different development stages.

Alberta has already finalised its regulatory framework: in 2010 it enacted Alberta Carbon Capture and Storage Statutes Amendment Act (Gagnon, 2012). This Act basically amends a number of provincial statutes to facilitate CCS. Alberta government has the authority to grant licences and to lease for the injection of CO_2. With respect to long-term stewardship the transfer of responsibilities back to the Crown (federal level) is foreseen after issuing a closure certificate. Before the issuance of this document, the lessee is required to contribute into a fund to cover the Crown’s province's assumed liability, the costs of monitoring the site and other post-closure costs. Further amendments to the aforementioned Act were developed by Carbon Sequestration Tenure Regulation from 2011 (AR 68/2011, 2011). In it, the process for obtaining pore space tenure rights for carrying out CO_2 geological storage is defined and the requirement to store in geological formations deeper than 1,000 meters below the surface is stipulated. The evaluation permit allows the permit holder to carry out activities to evaluate the suitability of a site for subsurface CO_2 storage. The permit is valid for five years and is subject to administrative fees and measurement, monitoring and verification requirements. The regulation establishes details about drilling the wells and evaluation and testing of these wells, and foresees an injection duration period of fifteen years. Lessees must submit a monitoring plan for approval by the Minister of Energy every three years. Closure plans must also be submitted for approval every three years. CO_2 storage operations will have to obtain other approvals, such as surface access and injection well licences. The Regulations from 2011 will expire on 30 April 2016 with the aim to be reviewed and amended, if necessary. Alberta Carbon Capture Storage and Funding Act from 2009 and the Carbon Capture Storage and Funding Act Regulation provide funding mechanism for the design, construction and operation of CCS projects.

Moreover, Alberta initiated a CCS Regulatory Framework Assessment, within which different working groups are identifying any other potential regulatory gaps associated with CCS deployment. Enhancements for issues such as geological site selection and closure criteria, post-closure stewardship fund inputs and monitoring, measurement, and verification requirements were recommended. The final report of the Regulatory Framework Assessment was planned to be ready by the end of 2012 (Gagnon, 2012). No further specifications have been found, though the date has passed.

In Saskatchewan, the Oil and Gas Conservation Act (Bill 157, 2010) has been amended to expand and clarify the provincial regulatory authority for CO_2 storage. With these legislative amendments and Oil and Gas Conservation Regulations from 2012, barriers for CO_2 storage operations have been lifted. The provisions in the amendment that relate to CO_2 injection and storage refer to: regulation of the injection, storage and withdrawal of substances, including CO_2 and other GHGs; revision and clarification of the term »substance«; regulation and measurement of the withdrawal and underground storage of substances (such as CO_2) from and to a well (IEA GHG, 2012).

British Columbia released its Natural Gas Strategy in February, 2012. CCS is recognized as one of possible climate solutions. It was established that a regulatory framework and amendments to existing legislation are needed, possibly in cooperation with the BC Oil and Gas Commission. Some gaps have been identified such as site selection, monitoring, measurement, and verification and long-term liability issues. Legislative amendments are expected for 2013 (Gagnon, 2012).

In Nova Scotia, they have just started the activities to enable possible deployment of a pilot CCS project (Gagnon, 2012). Both an onshore and offshore option for storage was considered by the research consortium. They have issued a set of reports which include among others also regulatory/legal reports and risk management roadmaps.

Canadian provincial regulations, where available, are founded on the existing oil and gas regulatory practice. As such, the provinces decided for updating their existing regulatory framework rather than developing a comprehensive integrated CCS framework. However, similar to the USA, the driver for CO_2 underground disposal operations in Canada are still enhanced oil/gas recovery operations and not CO_2 geological storage itself. Further progress in forming the regulatory regime on provincial as well as on federal level is foreseen when the outcomes of the Alberta Regulatory Framework Assessment initiative are available (Baker and McKenzie, 2011).

4.1.5 Regulations in Australia

In Australia national regulation regarding CCS activities offshore exist: Commonwealth Offshore Petroleum and Greenhouse Gas Storage Act from 2006 with some specific regulations from 2009-2011, The National Greenhouse Energy Reporting Act 2007 and The National Greenhouse and Energy Reporting (NGER) Regulations 2008 – 2011 (Parsons and Brinckerhoff, 2012). All documents concern monitoring issues as well as environmental and human health impacts. Measurements, Monitoring and Verification (MMV) responsibilities can be categorised into four phases: a) determination of suitability for injection and storage of CO_2, b) operational plan for injection and storage activities, c) reporting, monitoring and verification requirements and d) site closure, license surrender and post closure monitoring. Federal states (Victoria, Queensland, South Australia) however have adopted their specific Acts and Regulations to regulate onshore geological storage and Western Australia and New South Wales are progressing following the same process. Most documents agree on the focus of the regulatory results, i.e. a risk assessment approach and on a life span continuous monitoring and verification process based on an adequate monitoring plan. Differences in MMV regulatory frameworks between jurisdictions exist, for example, in the frequency of reporting, in terminology, and in levels of prescription. Some documents do not address all (most) MMV issues.

The documents on the technical framework and guidelines in Australia are limited in number and do not provide comprehensive details (such as EU guidelines do) on complying with or regulating MMV requirements (Parsons Brinckerhoff, 2012). The same authors summarize the existing frameworks and guidelines as follows:

- Guidelines for Injection and Storage of Greenhouse Gas Substances in Offshore Areas, Clean Energy Division, Department of Resources, Energy and Tourism, December 2011 which are detailed and specific to Offshore Commonwealth CO_2 geosequestration and thus would not necessarily be appropriate for other jurisdictions.

- Carbon Dioxide Capture and Geological Storage, Australian Regulatory Guiding Principles, Ministerial Council on mineral and Petroleum Resources, 2005 which set out some objectives for MMV legislative frameworks but no detail.
- The NGER Technical Guidelines for the Estimation of Greenhouse Gas Emissions by Facilities in Australia, which are intended to embody the latest methods for estimating emissions and will need to be consistent with chapter 5 of the IPCC Guidelines (IPCC, 2006). The guidelines acknowledge that methods for estimating fugitive emissions from the injection and the storage site have not yet been defined, but are intended for inclusion in future updates of the NGER Determination and these guidelines.

Australia is currently developing a national technical framework for the Measurement, Monitoring and Verification (MMV) of geologically stored CO_2 (Parsons Brinckerhoff, 2012). The authors studied the relevant literature, provided the key findings on the feedback from the stakeholder that were engaged in the activities, presented options for addressing the key issues associated with the development of a national MMV technical framework and provided conclusions on the level of support the development of a national MMV technical framework. Stakeholders' feedback addressed groups of key issues such as scope, context and function of the national MMV technical framework, level of prescriptiveness, development and revision of the framework, knowledge and terminology and compliance and confidence. It has been concluded that Australian Legislation generally focuses on key regulatory outcomes that the MMV programme must demonstrate. Differences in MMV regulatory frameworks between jurisdictions exist, for example, in the frequency of reporting, in terminology, and levels of prescription.

Fundamentally, the existing literature, Australian and international, supports the IEA representation of Core MMV Requirements. In general, the majority of Australian legislation for MMV appears to be more rigorous and prescriptive than those applied internationally. EU, USA and Canadian jurisdictions propose risk based monitoring plans, less prescriptive and fit for purpose. Parsons Brinckerhoff (2012) further observation was that each site is unique and that the monitoring technology selection depends on site specific characteristics. They also resolve that being prescriptive in technology selection could lead to less than favourable results, because not all approaches are applicable in all circumstances. Moreover, it is emphasized that there is no common definition of MMV The "narrow" interpretation would include exclusively measuring the composition of a CO_2 stream and monitoring the injection, storage, migration and leakage of CO_2. A "broad" interpretation could include assessment of the site characterisation of the geological storage formation and the impacts of CO_2 leakage on the environment, human health and other resources. Another issue is a common understanding of a technical framework for MMV of geological storage of CO_2 is not evident.

4.1.6 Regulations in other parts of the world

Many countries outside the EU, the USA, Canada and Australia have begun the process of developing the CCS strategy and national regulation frameworks. Various countries have achieved different levels of advancement. However, very few of the non-EU jurisdictions have taken steps to integrate wider environmental matters into their respective regulatory frameworks. At this stage, issues concerning measurement, monitoring and verification processes are not comprehensively addressed in national regulatory regimes in other parts of the world (Norway being one exception). International Energy Agency and Baker and McKenzie are reporting about the progress in the wider CCS area worldwide on the yearly basis (IEA, 2012; Baker and McKenzie, 2011).

4.1.7 International regulations

In this section the contents concerning monitoring of various international documents are described. It must be noted, that the high level content of most of these documents have been assimilated in the EU storage directive.

IPCC issued two documents (IPCC, 2005; 2006) relevant for CCS and for monitoring of CO_2 storage sites. The IPCC Special report on CCS (SRCCS) covers all aspects of CCS and as a result is fairly basic in terms of monitoring. However, it was one of the first documents on CCS that echoed a lot of response among professionals and general public. At the time of issuing the document, the injection into the water column was not yet prohibited. In SRCCS monitoring is recognized as an important compound of the entire CCS system along with a risk management strategy. Monitoring in the pre-injection, injection and long into post-injection phase was prescribed. An additional role of monitoring should be to estimate emissions from potential sources (i.e., injection wells, EOR operations, storage sites) to be included in the greenhouse gas (GHG) inventories (IPCC, 2005). Natural analogues are considered as an important source of information for the behaviour of the CO_2 underground, particularly when practical experiences are still scarce. Within issues related to health, safety and environmental risks of geological storage of CO_2, SRCCS concludes that the risks of CCS activities would be comparable to the risks of natural gas storage, enhanced oil recovery (EOR) with injection mediums other than CO_2 and deep underground disposal of acid gas, provided that there is appropriate site selection, management and monitoring. This conclusion relates to both offshore and onshore geological storage sites.

The specifically developed legal and regulation framework was not yet available in 2005. The authors emphasize long-term liability issues such as longevity of the institutions, knowledge dissemination, property rights etc. A monitoring, verification and reporting framework was foreseen, but not yet detailed.

The focus of the Guidelines (IPCC, 2006) is a national inventory of greenhouse gases in various sectors. In it, the description of potential monitoring technologies to monitor the behaviour of the storage complex during storage operations (and beyond) is given. Capabilities, detection limits, applications, costs, limitations and the maturity status (prior to 2006) of potential monitoring technologies are presented. The monitoring technologies are further divided according to the target (i.e., deep/shallow subsurface, flux detection from ground/water, detection of raised CO_2 levels in air/water/sea water, detection of leakage). The authors suggest how to properly characterize the storage site prior to any operations in order to identify possible natural leakage or migration pathways. The monitoring approach as well as the concept of a monitoring plan proposed here are basically the same as described later in the CCS Directive: "...site characterization, modelling, assessment of the risk of leakage and monitoring activities are the responsibility of the storage project manager and/or an appropriate governing body that regulates carbon dioxide capture and storage.“ (IPCC, 2006). However, the Guidelines refer several times to EOR, EGR and ECBM operations and suggest specific solutions, which are currently not covered in the CCS Directive.

The NSBTF group (2009) studied the applications, limitations and benefits of individual monitoring methods for offshore storage. They suggest some possible effective methods to be used to detect leakage and to define the leakage rates in offshore storage locations.

Offshore CO_2 geological storage activities need to comply with the London Protocol (IMO, 1996), which is a modernised version of the earlier London Convention (IMO, 1972) on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter and with the OSPAR Convention (OSPAR, 2007aIMO, 1992), the North-East Atlantic's equivalent of the London Protocol. The amendment to the 1996 London Protocol, which entered into force in 2006, adopts the approach of, banning all forms of disposal unless specifically allowed. Carbon dioxide streams from carbon dioxide capture processes for sequestration is included on the list of acceptable materials for dumping (the so called »reverse list«). As a result, carbon dioxide storage in sub-seabed formations have been endorsed provided that (1) disposal is into a sub-seabed geological formation; (2) the carbon dioxide stream is of high purity containing only incidental amounts of associated substances; and (3) no wastes or other matter are added for the purpose of disposing of those wastes or other matter (WRI, 2008).

London Protocol Specific Guidelines (IMO, 2007) were developed and are intended for use by national authorities responsible for regulating the dumping of wastes. In 2007, OSPAR issued Guidelines for Risk Assessment and Management of Storage of CO_2 Stream in Geological Formations (OSPAR, 2007b) with Annex 1 Framework for Risk Assessment and Management of storage of CO_2 streams in geological formations (OSPAR-FRAM, 2007). The aim of OSPAR Guidelines is to assist in the management of storage of CO_2 streams in geological formations in consideration of several aspects, including collection of necessary information (monitoring) and development of a strategy to manage uncertainties and minimise risks. Moreover the Guidelines provide general guidance for operators when applying for permits for the storage of CO_2 streams in geological formations. Both documents (London Protocol Specific Guidelines and OSPAR Guidelines) are specific in terms of risks associated with CO_2 storage in sub-seabed geological formations which include risks associated with leakage into the marine environment of CO_2 and any other substances in or mobilized by the CO2 stream and are closely related in many further aspects of risk management in general. In OSPAR-FRAM (2007) it is emphasised that the management of a CO_2 storage project during the project life cycle is an iterative process necessary for its continual improvement. An illustrative figure explaining the cyclic process of risk assessment and management during the entire lifecycle of a CO_2 storage project is presented (see Fig. 4-2). Monitoring shall be performed from planning up to the post-closure phase. In the planning phase, risk management is used to design preventive measures based on predictions derived in particular from the outcome of the risk characterisation stage. Risk management further defines the requirements for monitoring, during and after injection of CO_2 streams. The authors of OSPAR-FRAM express their concern about small leaks of CO_2 and incidental associated substances from the storage formation that may remain undetected, when the resolution of the available monitoring techniques is less than necessary to observe such quantity (OSPAR, 2007b).

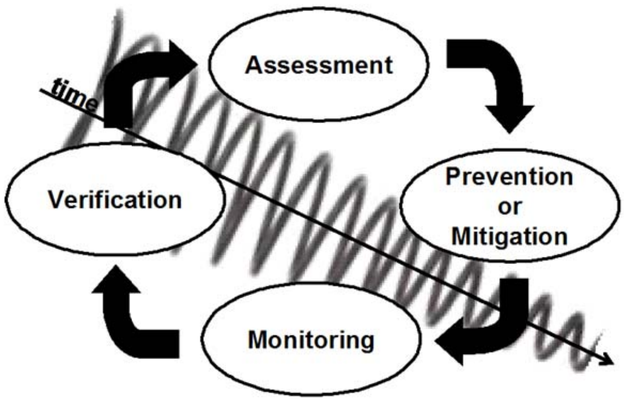

Fig. 4-2: Cyclic process of risk assessment and management during the lifecycle of a CO_2 storage project (OSPAR, 2007b).

The results of monitoring can lead to the identification of additional preventive and/or mitigation measures. After site closure the monitoring should continue, but its intensity may decrease and, eventually, “monitoring may be discontinued when there is confirmation that the probability of any future adverse environmental effects has been reduced to an insignificant level.” (OSPAR-FRAM, 2007).

Local and global aspects are addressed and over all timescales, but primarily at the local and regional scale and thus focus on the potential effects on the marine environment in the proximity of the receiving formations. Basically, it is required that the risks should be sufficiently described or quantified so that it is clear what variables should be assessed during monitoring.

The risk characterisation should lead to the development of an "Impact Hypothesis" which is an alternative approach to the one followed by the CCS Directive. Impact Hypothesis is a concise statement of the expected consequences of disposal. Based on it, environmental monitoring requirements shall be defined. Risk based monitoring programmes will need to be designed to test the Impact Hypothesis but also to clearly define objectives which would enable to trigger mitigation or remediation plans. A set of key parameters for monitoring is proposed. Further baseline information is required so that any deviations from pre-disposal conditions in the receiving area could be detected. The monitoring programme should allow to detect CO_2 migration and potential leaks over a large area. It is specifically required to monitor the seafloor and overlaying water to detect leakage of CO_2, or substances mobilized as a result of the disposal of the CO_2 stream, into the marine environment and to monitor marine communities (benthic and water column) to detect effects on marine organisms. OSPAR-FRAM specifies some possible remediation methods in case of leakage through well(s) and/or faults or fractures. Other monitoring issues such as monitoring objectives, what to detect, key parameters to be monitored, monitoring tools, frequency, updates of the monitoring programme etc. are similar to provisions for onshore CO_2 storage sites. Permitting procedures should take into account monitoring results and regular reporting.

The OSPAR Commission (2006) issued a report in which it focuses on appropriate monitoring and surveillance technology and methodology for the safe storage of CO_2. Geophysical techniques such as seismic methods and gravimetry should be used in a site specific manner to monitor the CO_2 storage and to enable the remediation of leakage. The report suggests the techniques which are based on decades of experience in the oil and gas industry. Direct measurements of fluxes may not be possible for off-shore deep sea geological storage of CO_2. Monitoring has therefore to rely on indirect methods, e.g. monitoring amounts and movement of CO_2 in the reservoir. Since some risks may be less severe for offshore storage sites compared with onshore ones, specific solutions concerning risk to humans and to ground water reservoirs are foreseen.

The OSPAR-FRAM document identifies several gaps in knowledge addressed to off-shore CO_2 storage sites (some are also relevant to onshore ones) at the time of issuing the document in 2006: "Further research is necessary in order to improve and adapt options for remediation, mitigation and monitoring, to improve predictions of exposure to CO_2 and incidentally associated substances and to improve the impact prediction on the effects on species and ecosystems as a result of leakage of CO_2 streams."

Det Norske Veritas coordinated a consortium which published a set of documents with the aim to accelerate the deployment of CCS projects, in particular geological storage of CO_2. In the CO2QUALSTORE documents (DNV, 2010a; DNV, 2010), a risk based approach to site selection and qualification of projects for CO_2 geological storage was used. The entire lifecycle of the project is considered. The documents are aimed at various users (i.e. developers, regulators, third parties) in five areas of application: guidance for implementation, information on best industrial practice, support for the implementation of the regulations, reference for verification and support to stakeholder communication. The primary intention of the guideline is to contribute to consistent implementation of CGS projects but also to help regulators to evaluate if a project is developed in accordance with industry practice and to support implementation of national and international regulations, codes and standards. Furthermore, the purpose of the guideline is to provide a basis for verification and validation. Independent verification can contribute to: demonstrate compliance; manage and minimise risks (and uncertainties); avoid future loss or liabilities; provide assurance to stakeholders; and secure a transparent, consistent and cost-effective process (DNV, 2010a). A generic workflow for CGS project activities is introduced in the guideline. For several project stages (operational stage being among them), a more detailed sub-flow is proposed with activity specific milestones and deliverables. CO2QUALSTORE documents cover a long list of issues for each stage (i.e. Screen, Assess & Select, Design, Construct, Operate, Close) (described in Appendix B of the guideline), including monitoring, verification, accounting and reporting (MVAR) plan to be performed in the operational stage. As far as monitoring and safety of operations are concerned, it is important to demonstrate adequate monitoring potential. Contingency and remediation plans shall be indispensable elements in the risk and uncertainty management. The CO2QUALSTORE consortium strongly suggests establishing a dialogue between the project developer and the regulator as early as possible in the qualification process. The objectives of such communication shall involve documentation requirements and performance targets for operational and closure stage. Here, it is beneficial to assess the potential impacts of the project and to agree on an MVAR program. It is essential to keep the regulator updated, to inform him on any uncertainty occurrence and/or alteration of predictive models. Recognizing the fact, that selection and quantification of storage sites should be an iterative process, any deviation from anticipated performance elements shall be reflected in the modification of performance targets and consequently of the MVAR program (and other relevant documents such as Storage Performance Forecast, Environmental Impact Assessment, Impact Hypothesis and Contingency Plan). Moreover, the MVAR program shall continue beyond the operational phase. Additionally, the CO2QUALSTORE consortium provided comparison of the guideline with the CCS Directive, with the proposed U.S. EPA rules and with the Australian offshore greenhouse gas storage bill. Links with relevant standards such as ISO 31000 are also demonstrated.

The International Energy Agency (IEA) released its CCS Model Regulatory Framework (MRF) in November 2010 (IEA, 2010). It is aimed at governmental bodies from diverse legal and regulatory environments to help them developing their own national regulatory framework. From this respect MRF is not very prescriptive and is not intended to provide detailed solutions. “Model text” is provided in order to facilitate countries to incorporate CO_2 storage issues in jurisdictionally appropriate way. MRF identifies 29 key issues as being critical in the process of regulation of CCS activities - monitoring, verification and reporting being one of them. One of the conclusions of MRF is that most of the CCS regulatory frameworks reviewed have a similar focus on regulating the storage part and all documents use the methodology for site assessment and monitoring provided by the IPCC Guidelines (IPCC, 2006).

Monitoring, verification and reporting requirements are addressed in the MRF as »CCS specific regulatory« issues. Main objectives for monitoring are addressed: appropriateness of operations, early warning, model calibration and validation and emission inventory. As far as monitoring requirements are concerned, storage authorization applications should include all data necessary for adequate monitoring in operational phase and beyond (results of site characterization, models, baselines, risk assessment etc.), as well as monitoring plan, corrective measures plan, closure plan and post-closure plan. Monitoring strategy and tools should periodically be refined and updated. In case of any incidental event, the storage authorization permit should be reviewed. The exact requirements will need to be determined by the relevant authority on a site or regional basis.

Environmental impact assessment as an integer element of the storage authorization application should identify and provide options for minimising local and regional environmental impacts related to storage. These should include monitoring of the entire storage site (sub-surface, injection facilities, surrounding domain). Baseline measurements should be considered. MRF recognizes the need for clarity in all risk assessment aspects; however, certain flexibility is also needed in project delineation when implementing any regulatory framework. During storage operations, the main regulatory consideration is compliance with agreed modes of operation, monitoring and reporting and inspections. When the operation phase ends, the relevant authority should be notified and provisions for the closure phase shall be enacted.

Monitoring requirements will also apply in case of transboundary CCS projects. The MRF is particularly targeted at countries that are currently developing comprehensive regulatory frameworks to facilitate demonstration projects and/or large-scale projects.

4.1.8 Comparison between the IEA-MRF and the EU CCS Directive

A similar comparison as was presented in section 4.1.2 can also be performed for the MRF regulatory framework. Based on the World Resources Institute (WRI) dynamic web-based tool, key issues are compared and the following similarities/dissimilarities between the EU CCS Directive and the IEA MRF were observed (WRI based tool):

- It can be recapitulated that both document are in agreement on many issues addressed such as: CO_2 stream constituents constraints, CO_2 definition and /or composition requirements, injection pressure determination, risk analysis and contingency plans, updates of models, phased permitting, financial responsibilities, flexibility in monitoring area delineation, choice of monitoring tools and sitting requirements focused on geological characterisation.
- Both models recognize that monitoring should be focused on the outcomes rather than on specifying methods. Comparing the predicted and actual behaviour of CO_2 in the subsurface and detecting any unexpected migration is also emphasised. However, the EU CCS Directive includes more detailed provisions for operational data collection.
- Both models include consideration of pressure within the storage complex. However, the EU CCS Directive focus is more general: instead of »area of elevated pressure«, the wording »pressure-volume behaviour and areal/vertical distribution of CO_2-plume« is used.
- Estimating capacity is recognized as part of site characterization in both the IEA MRF model and the EU CCS Directive, but only the later includes a specific mention of volumetric capacity estimates.
- In terms of monitoring duration the CCS Directive sets a 20 year minimum monitoring period (after site closure and before transfer to a competent authority) while IEA MRF contains only performance-based criteria for closure and no set duration. However, the CCS Directive's 20 minimum can be shortened if specific conditions are met. There is no upper limit on monitoring duration. In addition, the IEA MRF allows for minimum periods between cessation of injection and the issue of closure authorization. It can be summarized that both regulatory schemes remain flexible in setting monitoring duration.
- As far as financial responsibility updating is concerned, both regulatory models are in agreement. The EU CCS Directive requires periodic updating of the financial security, while the IEA MRF does not explicitly mention requiring updates of the mechanism on the "proof of the financial security," except in the case of a review of the entire storage authorisation, where a review of financial security of the applicant is implied.
- Minor differences exist in requirements for transfer of responsibilities. The CCS Directive provides the clarity on the transfer of responsibility from an operator to a competent authority and outlines the criteria. A default 20-year waiting period is foreseen. This is consistent with the IEA MRFs' criteria for the site can receive a certification of site closure. However, the IEA MRF differs from the EU CCS Directive in that it allows for these activities to include monitoring and verification and does not specify a default time period prior to transfer.
- Major dissimilarity is found in terms of storage site registration. The EU CCS Directive specifically mentions that a registry should be created and maintained by national governments. IEA MRF does not explicit mention such a registry.
- The EU CCS Directive is less strict about the presence of faults. It allows for the presence of faults and fractures, provided they are included in the geological model. However, the IEA MRF model stipulates that the storage complex should be "free of faults, fractures, wells or other features that are likely to allow unintended migration."
- Post-closure definition is not consistent in the two regulatory frameworks either. The IEA MRF has defined post-closure as a period after a demonstration of non-endangerment has been made and after the point at which the operator is no longer responsible for monitoring and verification,

while the EU CCS Directive defines the time period of post-closure to include time after a site is closed, and before and after responsibility of the site is transferred.

4.2 Current industrial-scale applications operating under CO_2 legislation

In the following sections the monitoring plans of a number of projects, that will operate under the umbrella of the most recent CCS legislation, have been analysed. It must be noted, that none of these projects is operational yet, and the advancement in applying for storage licenses varies widely. Nevertheless, it is instructive to see, how legislation has been interpreted and applied by the various industrial proposers in their applications. The analysis is limited in the sense, that it is only based on information publicly available. A number of potential storage sites in Europe have been analysed, of which the information on one Dutch and two UK projects is furthest advanced. Besides the European sites, also the Quest project in Canada has been analysed, since it received a license with minister's approval together with well license approval in 2012.

Where the Canadian Quest project is governed by the law of the province of Alberta, the European projects are governed by the EU Directive on CO_2 geological storage (and relevant Guidance Documents, including guidelines of DNV, 2010a), and by national laws implementing provisions of the Directive.

4.2.1 The Quest project (Canada)

In this section the monitoring plans for the Shell Quest project in Canada are analysed and discussed in terms of legislation. All information is based on documentation made publicly available through the website of Shell, including the appendix A of the project description documents describing the MMV plan (Shell, 2010).

The Quest project in Canada encompasses an integrated, full CCS chain, related to the exploitation of oil sands. Quest will capture more than one million tonnes of CO_2 per year from Shell's Scotford Upgrader, located near Fort Saskatchewan, Alberta. It is planned to transport CO_2 via a pipeline of about 80 km length in order to store in a highly saline sandstone aquifer of Cambrian age at a depth of about 2 km.

The starting point for the development of the monitoring (or MMV) plans has been the CO2QUALSTORE documents by DNV (2010a), where practical guidelines and examples are provided on how to develop this. The approach followed is risk based. The Bowtie Method (DNV 2010a) is used as an appropriate framework for a systematic risk assessment of events with the potential to affect storage performance. The monitoring plan includes multiple independent monitoring systems with the required sensitivity, response time, and scale to generate reliable early warnings of any potential loss of containment. It is linked to risks and to modelling in the following aspects:

1. Loss of conformance; where conformance means the behaviour inside the storage complex is consistent with model-based predictions. Therefore, lack of conformance is a project risk relating to the long-term liability (and to the site closure) and not a HSSE-critical risk - a high-level risk analysis is sufficient for the monitoring plan.
2. Loss of containment; this is a HSSE-critical risk, so a detailed and comprehensive approach to the bow-tie analysis is required. These are possible impacts on groundwater and hydrocarbon resources, soil contamination, CO_2 leaks into atmosphere, corrosion of legacy wells, CO_2 migration along an injection well, caprock integrity. The monitoring targets include measurements of any changes within the hydrosphere, biosphere, and atmosphere caused by CO_2 injected into the storage complex are sufficient to demonstrate the absence of any significant environmental impacts on an annual basis.

In both cases, two distinct types of preventative and corrective safeguards have been defined:

1. Passive safeguards: These safeguards are always present from the start of injection and do not need to be activated at the appropriate moment. These passive safeguards exist in two forms:
   a) Geological barriers identified during site characterisation;
   b) Engineered barriers identified during engineering concept selections.

2. Active safeguards: These are engineered safeguards, brought into service in response to some indication of a potential upset condition in order to make the site safe. Each active safeguard requires three key components in order to operate effectively:
   a) A sensor capable of detecting changes with sufficient sensitivity and reliability to provide an early indication that some form of intervention is required;
   b) Some decision logic to interpret the sensor data and select the most appropriate form of intervention;
   c) A control response capable of effective intervention to ensure continuing storage performance or to control the effects of any potential loss of storage performance.

From the risk assessment it can probably be concluded, that the major uncertainties for integrity of the reservoir are related to the (abandoned) wells penetrating the reservoir rock. Not only in terms of CO_2 leakage, but possibly for brine migration out of the reservoir rock along these wellbores. This has been taken into account in the selection of the injection area, where the distance to existing wells has been maximized. Currently the closest well is at a distance of 21 km, and the closest updip well at 31 km.

This risk factor has a strong influence on the storage complex and the extent of the storage Area Of Interest (AOI), that is guided by the expected extent of the pressure front after 25 years of injection at an average rate of about 1 Mt per year. The AOI is not the same as the storage complex, but is a larger area that needs to be monitored. The safety margin and pressure monitoring threshold value ensuring safe operations is based on scenario modelling of different subsurface models, that predict the start of brine migration upwards through the legacy wells far away (20 km) as a function of the anticipated pressure rises. As raised earlier in the section comparing the IEA-MRF and the EU CCS Directive, the EU CCS Directive is much less prescriptive about how to deal with the pressure increase. It does show once more, that pressure monitoring is the key technology to ensure safe storage.

This example also shows the importance of taking uncertainty into account for modelling. An important statement was made in the documents by Shell, stating that the models should represent the entire uncertainty range, but need to provide sufficient confidence at the same time to carry on the operations. Again an issue, that is addressed in the storage directive as well, but in a “soft” manner. The expectation is of course, that uncertainties will diminish as more monitoring data comes in during operations.

In the documented monitoring plans, at least three deep monitoring wells are to be drilled where continuous pressure measurements will be carried out. For each injection well three groundwater monitoring wells will be drilled (in order to conduct electrical conductivity measurements and annual fluid sampling and analyses), at least one of them close to the injection well. Geochemical signatures of brine from the storage site (Cambrian saline aquifer) have been identified and are to be used in order to detect a possible brine leakage into groundwater during fluid sampling and analyses. In all injection wells a distributed temperature sensing system will be installed.

In general the monitoring encompasses in-well monitoring to ensure integrity of the well and to monitor downhole parameters like pressure, geochemical monitoring at various levels from shallow and deep wells, geophysical methods to monitor the CO_2 extent and possibly pressure increases, and near surface monitoring.

As an early warning system for leakage, both geophysical and in-well techniques are used. In the Quest project monitoring from wells in the aquifer above the storage reservoir is also envisaged to detect anomalies in chemical composition of pressure increases.

Concerning geophysics, a baseline 3D surface seismic survey is planned. 3D VSP surveys are to monitor the CO_2 plume extent at the early stage of injection. Once the plume spreading becomes too extensive to be covered by the VSP measurements, a repeat 3D surface seismic survey will take over.

Other techniques operating at the surface include InSAR data designed to monitor surface heave induced by CO_2 storage and remote sensing data designed to detect environmental change (e.g. multi-spectral image analysis) are to be acquired. Also the line of sight CO_2 gas flux monitoring will be applied.

More details on the monitoring approach including a full list of techniques can be found in the documentation on the website.

4.2.2 The ROAD project (the Netherlands)

ROAD is an integrated, full CCS chain project initiated by E.ON Benelux N.V. and Electrabel Nederland N.V. (GDF SUEZ Group). It aims to capture 1.1 Mtonnes of CO_2 per year from flue gases of a new coal-fired power plant near Rotterdam in the Netherlands. From the capture unit the CO_2 will be compressed and transported through a pipeline: 5 kilometers over land and 20 kilometers across the seabed to the P18 platform in the North Sea, and injected into the depleted P18-4 gas field (Huizeling and van der Weijde, 2011, Arts *et al*., 2012), operated by Taqa.

As described in Arts *et al*. (2012), the gas field P18-4 is situated at approximately 3,500 m depth below sea level. The clastic reservoir rocks are part of the Triassic Main Buntsandstein Subgroup and the primary seal for the gas field consists of discomformably overlying siltstones, clay stones, evaporites and dolostones. The P18-4 gas field is located in a heavily faulted area, where reservoirs consist mainly of fault bounded compartments, which are (at least on production time scales) hydraulically isolated from their surroundings.

In principle the reservoir has been classified as suitable for CO_2 storage providing a stable long-term containment within the bounds of the storage reservoir. This conclusion is essentially based on the fact, that natural gas has been contained in this type of reservoirs for millions of years, the knowledge of the reservoirs obtained during exploration and production of the fields, the low pressure in the reservoir being brought back to the most stable situation of hydrostatic pressure after ending the CO_2 injection and the excellent sealing capacity of the cap rock..

The monitoring system proposed is designed to verify CO_2 containment and storage reservoir integrity especially while the storage facility is operating. This is achieved either by measuring the absence of any leakage through direct detection methods (for example at the wells), or by verifying indirectly that the CO_2 is behaving as expected in the reservoir based on static and dynamic modelling and updating thereof corroborated by monitoring data (for example pressure measurements in the reservoir). The design includes therefore the collection of data such as representative storage pressures and annuli pressures, injected volumes and gas qualities, well integrity measurements and seabottom inspection measurements.

The main component for monitoring deviations in expected behaviour indicating potential migration out of the reservoir consist of pressure (and temperature) monitoring. After proper history matching any deviations from the expected pressure trend (P/z curve) during and after the operational phase is a strong indicator for migration out of the storage complex. It is important to emphasize, that in the case of storage in a depleted gasfield, the quality of the predictive models is probably much higher, since the models have been calibrated to years of production history.

This example shows like for the Quest project the importance of pressure monitoring in the reservoir. Compared to Quest the main difference is, that lateral spreading of CO_2 is not an issue, since the reservoir is confined, and that pressure rise will only lead to bringing back the reservoir more to its original pressure prior to gas production. With the reservoir being underpressured currently, there is no real driving force to expel brine or CO_2 out of the reservoir.

Similar as for Quest, well integrity is an issue to be monitored, though in the case of ROAD only a single well (the injection well) penetrates the reservoir.

Particularly for the longer term after abandonment, when no access to the reservoir is possible anymore, inspection of the seabed using shallow geophysical surveys are envisaged to detect anomalous gas releases. Baselines are also planned to assess the current presence of shallow gas and its origin.

It is worth mentioning, that the ROAD project is the first project receiving the required positive opinion by the EC (EC opinion, 2012) stating its suitability for CO_2 storage and to receive its storage permit (in 2013). This European opinion is part of the procedure for granting a storage license in Europe under the EU CCS-Directive. The status of the monitoring plan is now, that the concept is accepted, but that a more detailed updated plan will be submitted prior to the start of injection.

4.2.3 The Longannet project (UK)

Both for the already cancelled Longannet and Kingsnorth projects non-confidential FEED studies were released by the British government (Kingsnorth Carbon Capture & Storage Project, 2010; UK Carbon Capture and Storage Demonstration Competition, 2011). All information in the sections on Longannet and Kingsnorth are based on the information from these FEED studies.

The Shell Longannet - Goldeneye project considered storage in a depleted gas field, with as target the Lower Cretaceous Valhall formation (Captain Sandstone member) at about 2 km depth (and to a lesser extent a secondary reservoir above, at a depth of about 1.5 km), in the central part of the UK sector of the North Sea. Each reservoir has a seal complex of mudstones and the seal complex above the primary reservoir also includes marls.

The monitoring plan comprises to a large extent the same elements as the ROAD project, namely:

- Environmental baseline monitoring using multi-beam echo sounding and seabed sampling and continuous tracer injection;
- Well integrity using pressure and temperature gauges, distributed temperature sensing (DTS), tubing integrity logging and seabed CO_2 detection below the platform;
- CO_2 injection conformance using pressure, saturation and flow monitoring;
- Lateral and vertical irregularity and plume conformance using time lapse seismic.

The main difference observed consists of the status of the time lapse seismic data. In the ROAD project, time lapse seismic data is considered as contingency monitoring, triggered by an irregularity observed on other monitoring data (essentially the pressure data), whereas at Goldeneye time-lapse seismic monitoring is part of the standard monitoring program. This can be justified by the fact, that in the shallower Goldeneye reservoir delineation of the plume in the reservoir is expected observable on the time-lapse seismic data, in contrast to the deeper P18-4 reservoir of the ROAD project.

Furthermore the seabottom imaging and sampling program seems more extensive at Goldeneye than for ROAD, which can be explained by the presence of existing pockmarks at the seabottom at Goldeneye and by the presence of seven abandoned wells in the area. These are absent in and above the P18-4 reservoir of ROAD.

The last major difference consists of the number of injection wells, originating from a conversion of the five existing gas production wells into injection wells. One of these wells will serve as a monitoring well at an early stage of the project to see the saturation front passing by. At ROAD the P18-4 reservoir is spatially much more confined by faults, with no additional wells penetrating the reservoir. The only well partially used for monitoring will be the P18-1 well, which penetrates the neighbouring P15-9 field. Regular checks for CO_2 contents might be taken, as well as pressure measurements to investigate potential (though highly unlikely) communication between the two fields.

Otherwise the philosophy at Goldeneye and P18-4 (ROAD) is highly comparable in the sense, that the plan aims essentially at detecting irregularities and then triggers a more extensive contingency monitoring program.

Selection of the monitoring technologies at Goldeneye is based on the following factors: risk relevance, measurability, operational constraints, competitiveness and proven technology.

The Bowtie Method (DNV, 2010a) as well as Shell's own risk matrix are used for a systematic risk assessment of events with the potential to affect storage integrity and performance.

The program complies with the high level requirements of the storage directive and its implementation in the UK and addresses the EU ETS MRG guidelines as well, since leakages for the full chain are addressed. The shallow seabed monitoring of the Longannet project addresses comprehensively the OSPAR guidelines.

4.2.4 The Kingsnorth project (UK)

As mentioned in the previous section, all information in this section results from an analysis of the published FEED study on the Kingsnorth project.

The EON Kingsnorth project considered storage in the depleted Hewett gas field, again a Bunter Sandstone formation at about 4 km depth, in the southern part of the UK sector of the North Sea. The demonstration phase of the project was limited to a maximum of 20 million tonnes of CO_2 and is required to be completed by 2029. Injection of CO_2 was expected to be performed entirely in gaseous phase for the duration of the demonstration phase.

Like for the P18-4 reservoir of the ROAD project, the targeted Lower Bunter reservoir does not have an active aquifer support and will in principle be underpressured at the start of injection. There is no connection (expected) between the lower and upper Buntsandstein reservoir. Currently the inclusion of the Upper Bunter in the storage complex is under consideration, since this reservoir represents a potential CO_2 storage site as well. Note, that the Upper Bunter reservoir does have active aquifer support. For the design of the monitoring plan, inclusion of the Upper Bunter reservoir has been taken into account as much as possible.

Below the Bunter reservoirs are potential reservoirs separated by the Lower Bunter shale and sealing sections of the Zechstein formation. Communication between these lower reservoirs and the target reservoir has been identified as an issue to further investigate, particularly through wells penetrating the lower reservoirs and plugged at the level of the seal between the two reservoirs.

Above the Upper Bunter various other sealing formations, that can act as secondary seals, have been identified.

The monitoring plan is in a very early stage of development, and it was mentioned, that refinement was envisaged prior to the start of the project. Therefore no references to remediation methods are made at this stage yet.

The monitoring plan is risk based, with as main risks identified:

- Wells (with old/exploration wells a greater risk than new drilled wells);
- Faults and Fractures (induced by injection);
- Upper Bunter caprock seal leakage;
- Upper Bunter aquifer dissolution/mixing;
- Upper Bunter aquifer ingress into Lower Bunter.

For each of the issues, parameters and measurement needs have been identified and the relevance of each monitoring method has been detailed for different scenarios. The scenarios include:

1. Injection of high pressure CO_2 into Low Pressure Reservoir: replacement of residual, low pressure, hydrocarbon gas by higher pressure CO_2 in the Lower Bunter;
2. Injection of Dense Phase CO_2 into the Upper Bunter: replacement of residual low pressure gas by dense phase CO_2 in the Upper Bunter;
3. Completed injection into Upper Bunter and Lower Bunter, pre abandonment;
4. Completed injection into Upper Bunter and Lower Bunter, post abandonment.

For these scenarios monitoring plans have been detailed out further based on measureable parameters.

From the technological perspective, a full overview has been made of possible monitoring techniques including their sensitivity and accuracy. The current monitoring program proposed (but still to be detailed further) is based on bringing together the identified risk based monitoring parameters and the technical monitoring feasibility.

It encompasses the following essential monitoring programme: continuous measurements of pressure, temperature and flowrates for all well heads, downhole pressure and temperature measurements for all wells; CO_2 sampling on the seabed and at the injection facility during the operational and post abandonment phase; 4D baseline seismic, repeated seismic on estimated time schedule (e.g., every 5 years), microseismic (optionally together with vertical seismic profile, VSP) and wireline logging.

A number of recommended monitoring techniques, that reduce the risk associated with unplanned migration localisation, have been identified: for selected wells techniques as distributed temperature sensor, casing strain detection, micro-seismic/in-well geophones (close to legacy wells or faults with highest reactivation risk) and optionally time-lapse controlled source electromagnetic methods (CSEM) are proposed.

Finally the use of dedicated monitoring wells is mentioned, though not firmly included in the proposed monitoring plan at this stage of the project.

The most striking difference of the monitoring program proposed for Kingsnorth compared to ROAD is probably the stronger emphasis on geophysical monitoring (time-lapse seismic, CSEM) from the surface to track CO_2 in the reservoir and the use of microseismic monitoring. Currently not sufficient detail is available on the expected responses of both monitoring methods in terms of monitoring the CO_2 injection processes in the reservoir.

4.2.5 The Jänschwalde project (Germany)

The Jänschwalde, integrated full CCS chain project of Vattenfall, now completely cancelled, was originally supported by the EEPR, like ROAD and a number of other European demo projects.

Approximately 1.7 million tonnes of CO_2 was planned to be captured from a lignite-fired power plant in NE Germany, transported via a pipeline and stored in an onshore saline aquifer of Bunter Sandstone at a depth of about 1.3 km.

The non-confidential FEED study (CCS Demonstration Project Jänschwalde, 2011) does not include a detailed monitoring plan, rather the scope of the site appraisal/preliminary characterization and (some) baseline surveys. Four deep and three shallow monitoring wells were to be drilled, 3D and 2D seismic and VSP to be shot and hydraulic tests of injection and extraction of brine were planned. Groundwater monitoring was designed, based on comprehensive archive data, to assess the possible impact of CO_2 injection and brine displacement on groundwater resources. The baseline groundwater monitoring was going to be re-evaluated and repeat campaigns were foreseen on an annual basis.

The relation between monitoring with risks and with modelling was not presented explicitly in the non-confidential FEED study, but a statement was made that the DNV CO2QUALSTORE JIP guidelines were to be followed.

4.2.6 Other EEPR projects (Poland, Spain, Italy)

For completeness, the status of the three other remaining EEPR funded projects in Europe is mentioned here. However, no clear published material concerning the monitoring plans for the industrial-scale application of CO_2 storage for these projects sites is available to the knowledge of the authors. The PGE Bełchatów project in Poland has been suspended and recently announced as terminated. About 1.7 million tonnes of CO_2 was planned to be captured from a new CCS-ready block of a lignite-fired power plant in central Poland, transported via a 140 km pipeline and stored in an onshore saline aquifer of Jurassic sandstones at a depth of about 1 km. The project stopped just before the full characterization and baseline monitoring of the selected site. No detailed description of the monitoring plan for the selected site was published. More information can be found at the website of the PGE Bełchatów project (2013).

The Compostilla project in Spain includes at this moment no industrial-scale application of either storage or monitoring, but the ongoing R&D work includes a storage pilot (planned injection of about 20,000 tonnes of CO_2) with a monitoring network within (a part of) an area where the demo storage operations are planned (after the Global CCS Institute website and Dios, 2013). No detailed description of the monitoring plan for the industrial-scale application of CO_2 storage can be found currently.

The Italian CCS project of Porto Tolle by Enel, of similar magnitude as these mentioned above, includes offshore storage and no detailed description of the monitoring plan for the industrial-scale application of CO_2 storage can be found currently.

4.3 Similarities and differences in approach

4.3.1 Similarities in approach

Though it is not mentioned explicitly, both provisions of the Directive on the geological storage, or rather the relevant Guidance Documents (Guidance Documents 1-4, 2011), and legislation of the province of Alberta in Canada require similar approaches for onshore sites regarding measuring properties of the stream delivered to the storage site, conditions within reservoir, or the use of surface monitoring and environmental methods.

In all cases the monitoring approach is risk based, with an emphasis on early warning systems and pressure monitoring. Monitoring of well integrity (both existing and new wells) is key. The use of time-lapse seismic data seems almost standard, even if detectability of CO_2 in the reservoir in some cases can be questioned. Only the ROAD project seems to be more explicit on the use of time-lapse seismic data, in the sense that it is considered as a contingency monitoring method. In other words, only in case of irregularities detected by other methods, time-lapse seismic data acquisition will be considered.

4.3.2 Differences in approach

The main difference in the presented approaches is essentially related to the project being onshore or offshore. In case of onshore projects, groundwater (and soil) protection seems to be paramount, which is not necessary for offshore projects where only seabed soil/sediment sampling is planned (for example Longannet seems to follow the OSPAR guidelines explicitly).

The Kingsnorth project clearly went further in defining alternative geophysical monitoring besides 4D seismics. Both CSEM and gravity are mentioned in the documentation as potential methods. It must be noted though, that modelling studies were not undertaken yet to investigate the expected performance.

A striking difference between the Canadian Quest project and the EU projects is the more explicit definition of the Area Of Interest, based on the expected pressure footprint. In most European case studies this area is less stringently defined, although in practice the same considerations are taken into account.

Furthermore the notion of uncertainties in models seemed to be mentioned more explicitly in the Canadian monitoring plans.

4.3.3 Compliance with the storage directive

Overall all monitoring plans seem to comply with high-level requirements of the storage Directive.

However, most of these plans are not defined in detail yet, so it is hard to outline gaps either in the monitoring plans or in the directive.

A key issue, that deserves more attention is probably the handling of uncertainties, both in models, in parameters and in monitoring measurements. The definition of threshold values to determine whether deviations are serious irregularities is not straightforward taking all the uncertainties into account.

4.4 Main differences with gas storage, or other oil- and gas operations

Obviously hydrocarbon storage operations can be labelled as a more mature technology, with experiences dating back for almost a century (Perry, 2004). At least in case of the US and the EU, monitoring of hydrocarbon storage uses a number of quite similar monitoring approaches and methods as proposed for CO_2 storage. These include PVT inventory verification, surface and deep well monitoring (and reservoir testing), gas sampling and tracing and last but not the least, caprock integrity evaluation. In case of natural gas storage well monitoring (wells penetrating the reservoir formation and potable aquifers) seems to be the most important monitoring method for leak detection (Perry, 2004).

4.5 Conclusions

This chapter provides an overview how monitoring is addressed in legislation and directives, how guidelines and protocols have been developed to interpret the legislation and how some of the early integrated industrial scale CCS projects have incorporated monitoring plans in their permit applications.

Regulatory regimes in different countries across the world vary. Some countries chose an integrated approach to CCS regulation (i.e. to develop stand-alone legislation), while others decided for a piecemeal approach (i.e. basically amending/updating existing laws and regulations). However, many regulatory regimes took the IPCC Special Report (IPCC; 2005) and IPCC Guidelines (IPCC, 2006) as a starting point. The EU and Australia can be considered the leading players in establishing CCS related regulation frameworks, closely followed by the US and Canada.

A comparison of regulatory documents from different jurisdictions showed, that the objectives for monitoring are similar in terms of tracking the injected fluid in the subsurface and to monitor key risks related to HSE. There is also a common denominator, that monitoring plans should be risk and objectives based, site specific and non-prescriptive in terms of technologies applied. While the EU regulation is entirely focused on emissions reduction objectives, the USA regulation seems more focused on enhanced oil production (EOR) and so called CCUS (carbon capture, use and storage). EU legislation does accept combined EOR and CCS operations, though strictly regulated through the CCS Directive. Moreover, EU legislation requires permanency of stored CO_2, while the US (and Canadian) legislation seem to accentuate stronger the utilisation of injected CO_2. In all cases long-term liability provisions need further revision and consolidation.

After reviewing the EU and other international/national legislation related to monitoring we can summarize, that regular reporting of the results of monitoring to some kind of competent authority is always requested. In order to verify the content, the performance quality and the relevancy of specific operational procedures and/or corrective measures taken, it will be crucial the reports are inspected by a competent authority. In Annex V of the ETS Directive minimum competency requirements for the verifier are stated. However, the EU CCS Directive does not deal with issues concerning verifier's competency. It may be worth considering the introduction of standards for verification bodies regarding their knowledge, experiences, independency etc. This may result in the introduction of an accreditation procedure for verifiers under the CCS Directive at different levels (national, international).

The permanency of containment of CO_2 underground, other than in case of most other subsurface uses, implicates that monitoring data shall be acquired for much longer periods. This issue is related to the handover and specific liability requirements of the state where CCS takes place.

Data retention and ownership of the information from monitoring reports are mentioned in Guidance Document 2 and possible solutions are offered. For example in Europe at present, it is up to the Member States to choose which approach to follow and to establish appropriate regulations concerning the access to and the rights to use the information. It is important to balance between proprietary rights and the transparency for public. At many events (conferences, workshops, panel debates etc.), the dilemma on whether the results of monitoring shall be communicated to a general public arises. Eminent discussion participants (scientists, stakeholders, regulators) are of the opinion that openness and transparency should be a top priority. At least two reasons exist for such conviction: firstly the ability to develop new knowledge through circulation of information and secondly to build public confidence in CCS technology. However, how, who and to what extent to communicate the monitoring results (and other information on CCS in general) remains ambiguous.

Only a limited number of examples of industrial scale integrated projects falling under recent CCS legislation are available. A few of them have been evaluated in this document. Though differences can clearly be identified, all examples follow a similar risk-based approach for defining the monitoring plan.

In all cases wells were identified as potential hazards, either in terms of potential CO_2 leakage along the wellbore, or induced brine migration by the elevated pressures in the reservoir. Monitoring tecniques selected depend on the geological setting and on the type of wells. Nevertheless, the monitoring plans do show many similarities.

Probably an issue, that needs to be dealt with in more detail, is on the handling of uncertainties. As stated earlier: “Models should represent the entire uncertainty range, but need to provide sufficient confidence at the same time to carry on the operations.”

5 DIRECTIVES AND REGULATIONS RELATED TO STORAGE SITE REMEDIATION

Remediation measures are applied in case a significant irregularity in the behaviour of a storage site or a leakage of CO_2 from a storage site occurs. They can be divided into three categories, depending on the nature of the event. The first category applies to wells and includes well intervention techniques that can mostly be based on proven practice from the oil and gas industry. The second group refers to leakage through geological pathways like caprock failures or faults. In this case the remediation measures usually involve injection and pressure management modifications and/or use of low-permeability "healing" materials. The third case is leakage into overlying aquifers (including potable groundwater resources and near-surface structures) where techniques common in hydrogeology and pollution control are considered.

A special group of newly developed techniques, directed specially at remediation of CO_2 storage sites, include application of special materials (special cements, self-healing substances, etc.) or specifically tailored aquifer management techniques. These techniques are the subject of intensive on-going research and development, and further improvements in this field are expected in the near future.

Remediation measures are an integral part of regulatory regimes for CCS in all relevant countries and regions where CCS activities are on-going or planned. The CO2QUALSTORE guideline (Aarnes et al., 2010) considers contingency and remediation planning an essential part of the risk and uncertainty management, providing a systematic approach to the issue. The European regulatory framework is based on the EU CCS Directive (2009) and Guidance Documents 1 and 2 (2011). The key instrument is the risk-based and site-specific corrective measures plan which has to be prepared by the storage site operator as part of storage permit application.

The international comparison shows that most of the regimes are based on similar foundations, closely linking risk assessment, monitoring and remediation measures into one mutually interconnected package. The European and U.S. legislations appear to be the most detailed and most elaborated.

The main aim of geological storage of carbon dioxide is to safely and permanently store the captured CO_2 and prevent it from migrating out of the storage formation and entering the atmosphere. It is expected that well selected, sufficiently investigated and carefully operated and monitored storage sites will meet this target thanks to the various trapping mechanisms existing in the storage formation.

It is, however, important to consider the probability that CO_2 may escape out of the storage formation, migrate within the storage complex or even leak out of it into the shallower sub-surface or up to the atmosphere. Although such an event would cast in doubt the CCS technology and may also adversely affect the public acceptance of the technology; if it can be demonstrated that any such event can be remediated in a simple and cost-effective way, this would be very important for policy makers, regulators, site operators and the general public (Kuuskraa and Godec, 2007). It is, therefore, very important to have sufficient knowledge about what can be done if leakage from the storage formation is detected. This chapter provides a brief summary of available remediation techniques and an overview of regulatory regimes related to remediation of leaking storage sites both in Europe and worldwide.

5.1 Site remediation measures

Remediation measures (often also called corrective measures) are applied in case a significant irregularity in the behaviour of a storage site or a leakage of CO_2 from a storage site occurs. The method and type of remediation required will be dictated by the nature of the significant irregularity or leakage. The main generic leakage pathways and irregular behaviour types can be summarised as follows (Guidance Documents 1and 2, EC, 2011a, b):

- Geological
  - CO_2 leakage due to caprock failure – caprocks may be ineffective in containing CO_2, unexpectedly absent over part of the storage area, or degraded as a result of geochemical reactions and/or hydrocarbon depletion;
  - CO_2 leakage via faults and fractures - leakage through natural geological pathways, or resulting from CO_2 injection and build up in the reservoir, hydrocarbon depletion, natural or induced seismic activity;
  - Overfilling beyond spill point - structural spill out of the trap, where the reservoir is smaller than expected and/or over-filled;
  - Updip leakage - leakage through high permeability intervals, of particular relevance to stratigraphic trapping or migration assisted storage.
- Manmade
  - CO_2 leakage through wells and boreholes – caused by well integrity issues;
  - Pathways associated with mining activity.
- Other
  - Risks relating to groundwater including effects that arise directly from the effect of dissolved CO_2 in the formation water, including heavy metal mobilisation;
  - Indirect effects from groundwater contamination by displaced brine;
  - Oil or gas leakage or emissions that could result from the displacement of hydrocarbons in underground formations by CO_2 injection and movement;
  - Any risks relating to movement of other hazardous components such as H_2S;
  - Ground movement, uplift and/or subsidence;
  - Natural seismicity, seismic hazards and tectonics, including exposure earthquakes;
  - Effects from sabotage or terrorism.

A significant distinction needs to be made between remediation measures that can be applied to the two major types of leakage pathways - geological and manmade. While corrective measures and repairs to wells (most frequent manmade pathways) are often technically feasible, the effectiveness of corrective measures and potential of restoring the geological system in general is limited. However, corrective measures that involve early interventions and modifications to injection operations will usually be beneficial (Guidance Document 2, EC, 2011b).

In principle, wells can be accessed, allowing tools to be run or operations to be performed in order to repair leakages or significant irregularities of the wellbore and its immediate surroundings. Unlike wells where the location of any anomaly is usually known and pinpointed, geological anomalies are more likely to be three-dimensional problems, of significant vertical and/or lateral extent, and where the precise location of any failure points is uncertain. In addition flaws in the geological system can typically be corrected only when wells are penetrating the affected zone. This seriously reduces the options to repair the geological anomalies, making early detection through monitoring and early intervention important. Hence, it is important to carefully integrate the monitoring plans and activities with the corrective measures. Monitoring should be used to detect anomalies and trigger early mitigation measures.

5.1.1 Remediation of leakage through wells by well intervention

CO_2 leakage from the storage reservoir through operating and especially orphaned, abandoned and even old wells is considered to be a potential leakage pathway for a CCS project, which is worth considering carefully (Ide *et al*., 2006). The possible reasons why a well may be leaking are (Kuuskra and Godec, 2007):

- The well was poorly designed or completed, allowing gas migration along the well or wellbore;
- An unanticipated well failure occurred (such as parted casing);
- When abandoned, the well was inadequately plugged and sealed.

In contrast to the natural geological system, the wellbore system is an engineering structure. A general downhole well configuration consists of multiple casings, usually made of steel. In many cases the annular space between geological formation and the steel casing is (partly) filled with cement. Injection or production wells often are equipped with injection or production tubing. Abandoned wells will be sealed with several cement and potentially mechanical plugs (Guidance Document 2, EC, 2011b).

Wells drilled for the purpose of CO_2 storage operations can be designed, completed and abandoned according to requirements applicable to long-term containment. Even previously drilled wells, configured without taking into account future CO_2 storage purposes, can often be modified to comply with requirements. The main problem lies with already abandoned wells that are no longer accessible. Well flaws leading to leakage through or along the wellbore is nothing new. The oil and gas industry has decades of experience and offers standard techniques as well as advanced technologies to repair leaks in the various parts of a well. If required, injection tubing and packers can be replaced, leaking casing can be repaired, or cement can be squeezed behind the casing. In the case of a blow-out, standard oil and gas industry techniques are available to 'kill' a well (e.g. injecting heavy mud/weighted brine into the casing). A good overview of well remediation measures is provided by Meyer (2007).

In case of *leakage of injection tubing*, first of all the well must be "killed". After killing the well e.g. by injecting heavy mud or weighted brine into the casing, the failed tubing string needs to be pulled out of the hole. At the surface the tubing can be hydrotested, after which the leaking tubing joint can be replaced. In case no leaks are detected, failure may have occurred in a tubing collar which was remedied as the tubing was rerun.

Leakage of casing is usually caused by a damage to casing steel due to, e.g, mechanical erosion or chemical degradation. There are many measures available to repair such damage (Meyer, 2007):

- A squeeze job, forcing cement or a chemical sealant through leaks or intentional perforations into specified locations of the annulus, may prevent communication between the inside casing and casing-formation or casing-casing annuli.
- Alternatively, a new liner (either fiberglass or steel) can be placed over the leaking section, effectively covering the leak.
- A special application of the latter involves the use of expandable tubulars. This technology enables expansion of the casing or liner by up to 20% in diameter after being run down-hole. For this purpose, an expansion tool that exceeds the inner diameter of the tube by the required amount of expansion is forced through the pipe.

In case of *leakage behind the casing* due to lacking or inadequate cement sheath, several methods can be applied to remediate the cement sheath and achieve isolation (Arts *et al*., 2009):

- Squeeze cementing involves the process of forcing by pressure cement slurry into a specified location in a well through perforations in the casing or liner. Once the slurry encounters a permeable formation, the cement solids are filtered out of the slurry as the liquid phase is forced into the formation matrix in the form of cement filtrate. Squeeze cementing is a remedial cementing technique used to repair flaws in primary cement or damage incurred by corrosive fluids. A properly designed squeeze-cement operation will fill the relevant holes and voids with cement filter cake that will cure to form an impermeable barrier. Also chemical sealants are available for squeeze jobs.

- Block cementing is used to isolate a permeable zone. To this purpose the sections above and below the target formation are perforated and squeezed.
- A circulating squeeze involves circulating cement between two sets of perforations, isolated in the string by a packer or cement retainer. The operations consist of an initial circulation with water or acid as receding fluid, a subsequent circulation of the interval with a cleaning wash fluid, and pumping and displacing of the cement slurry. This method is a low pressure squeeze. Except for some increase in hydrostatic pressure resulting from the increasing cement column in the annulus, no pressure build-up is associated with this type of cement squeeze. The exact amount of required cement is unknown, leading to the use of excess cement. This holds the risk that cement slurry enters the casing above the packer or retainer. If this cement would cure, the tubing may become stuck in the hole.
- Alternatively, expandable tubulars could be applied on the outside of the casing.

Leaking injection and observation wells where repair is impossible should be plugged and abandoned. The same goes for leaking old abandoned wells that need to be re-plugged. Procedures of well abandonment are well-known from the oil and gas industry (Randhol *et al*., 2007).

5.1.2 Remediation of leakage through geological pathways

In case a leakage occurs as a result of an unexpected flaw in the geological system, this is most likely to result from caprock failure, faults and fracturing, overfilling the storage reservoir beyond spill point or up-dip leakage. Due to the limited access to the geological structures at depth, the possibilities to correct or repair the containment capacity of the system are usually restricted to a general set of measures associated with wells and injection operations management (Guidance Document 2, EC, 2011b). Remediation measures can be deployed either to reduce or prevent further leakage or to try to correct and remediate the leakage itself, and any impacts at surface.

There are several viable techniques based on stopping the pressure increase in all or part of the reservoir, or reducing the pressure. The main techniques are (Guidance Document 2, EC, 2011b):

- Limiting CO_2 injection rates and pressure build-up in specific wells or across the site, either temporarily or permanently. This would reduce pressure build-up in all or part of the reservoir and may be used to address caprock related issues and fracturing. This type of measure is straightforward to apply.
- Reducing the reservoir pressure by extracting CO_2 or water from the storage reservoir or complex. By decreasing the pressure gradient this may help cease or reverse the impacts of faulting, fractures, spill and any migration out of the storage complex. This can be done in a number of ways:
    - Reduction of CO_2 injection pressure (e.g. by using lower injection rate, or more injection wells);
    - Stopping CO_2 injection;
    - Producing back injected CO_2 from the storage reservoir/plume (actively reducing reservoir pressure) and either controlled venting or re-injection in another site;
    - Peripheral extraction of formation water or other fluids;

- Increase of reservoir capacity and steering CO_2 in favourable directions by hydrofracturing (this would create pathways to develop and access new compartments of the storage reservoir away from leakage areas; by expanding the storage container, the pressure will decrease).

- Extraction of CO_2 at or near an identified leakage point, zone or pathway (in contrast to extraction from storage reservoir). This will depend on pinpointing leakage zones and is likely to require new targeted extraction wells. In some cases it may be possible to intersect leakage zones with existing wells by:
- Sealing regions where leakage is occurring such as identified fault or caprock leakage pathways in limited areas by injecting low-permeability materials (e.g. foam or grout).
- Increase of pressure in formations upstream of CO_2 leakage, creating a hydraulic barrier (decreasing pressure gradient).

One should be aware of the status and limitations of different techniques and methods. While several of these measures involve commonly employed practices in oil and gas industry or environmental remediation, some comprise innovative concepts or include expensive operations such as drilling of new wells. The natural geological system contains many heterogeneities and discontinuities. As a result, leakage is not easily undone, so that choices to repair are limited and rather tend to be directed at mitigation. Furthermore, the effectiveness of all the measures is strongly determined by the site-specific geological system, the nature of the actual leakage or irregularity and the status of the specific method or technique (Guidance Document 2, EC, 2011b).

5.1.3 Remediation of leakage into overlying aquifers

Leakage of CO_2 into groundwater aquifers (no matter if this is through geological or man-made pathways) may degrade valuable groundwater resources, including drinking water reserves, may pose a risk to human health if hazardous trace metals dissolve into groundwater, and may interfere with agricultural activities. Although there is a significant experience from groundwater remediation of contaminants, CO_2 poses many unique challenges. In principle, three main remediation techniques can be applied (Esposito and Benson, 2012):

- Remediation using extraction wells. After the CO_2 leak into the aquifer is stopped, a vertical or horizontal well is drilled that penetrates the CO_2 plume. After the well is drilled, the extraction of fluid begins immediately. The well operates until the amount of CO_2 remaining in the reservoir is small or meets specific remediation specifications.
- Remediation using water injection wells. The second remediation technique is to inject water into the aquifer with the goal of halting the movement of the separate CO_2 phase through capillary trapping and dissolution. If more water is injected, all the CO_2 can be dissolved eventually in the water (Fig. 5-1).
- Remediation using injection and extraction wells. This technique represents a combination of the previous two methods. It may bring the best results if multiple extraction and injection wells are combined in a suitable scenario.

A special case of remediation measures, so called hydraulic barrier, can be used to stop a CO_2 leakage from the storage formation into an overlying aquifer. The underlying principle is to counter the driving forces of the migration (natural CO_2 buoyancy and injection-induced overpressure) by increasing the pressure over the leak through brine or water injection into the overlying aquifer (Fig. 5-2). This technique is commonly used as a preventive or corrective measure in pollution engineering, e.g. in order to protect the drinking water against salt water intrusion in coastal areas. For CO_2 leakage remediation, however, the technique needs to be applied much deeper (Réveillère *et al*., 2012).

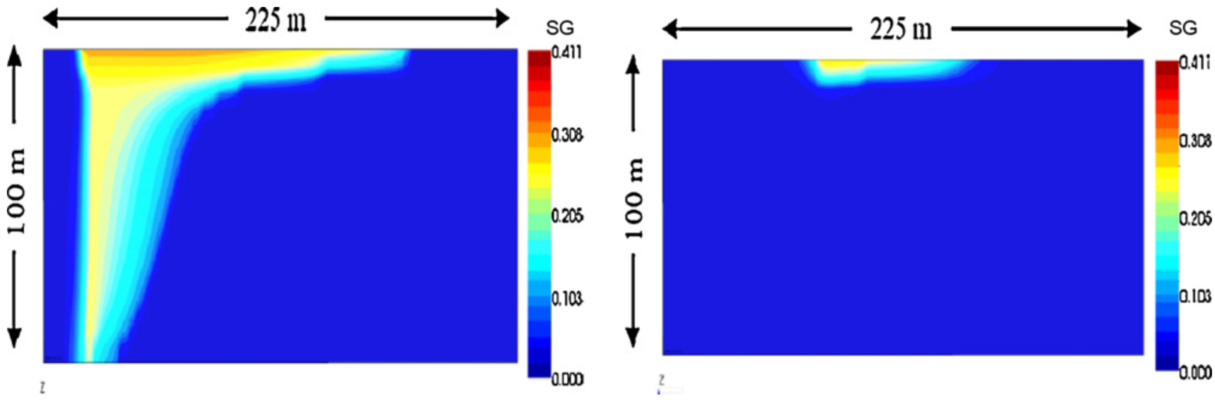

Fig. 5-1: The CO_2 gas saturation simulation results in vertical cross-section for a remediation scenario with one water injection well (left-hand margin of the section, flow rate of 25 kg/s) after 2 days (left) and 33 days (right) depicting the reduction in the gaseous phase plume size (Esposito and Benson, 2012).

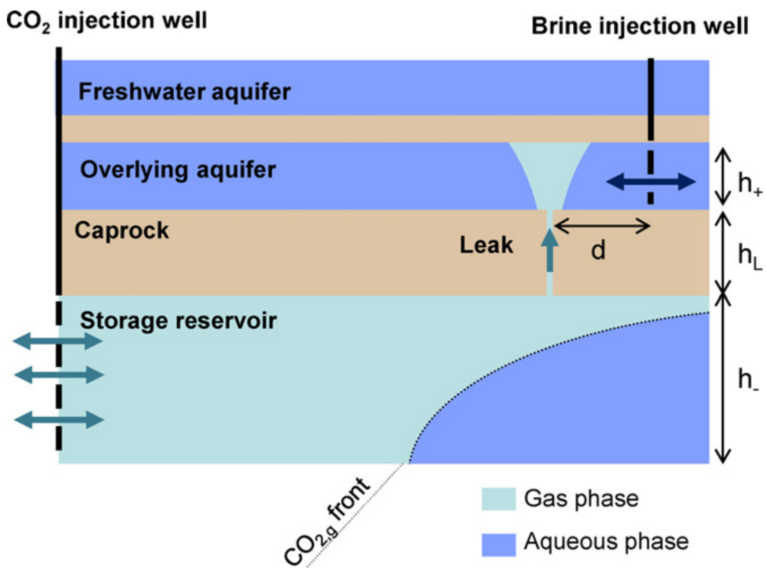

Fig. 5-2: Principle of CO_2 leakage remediation using the hydraulic barrier technique (Réveillère *et al*., 2012).

5.2 Regulatory regimes and guidelines relevant to CO_2 storage remediation

A systematic approach to the selection and qualification of storage sites and projects for CO_2 geological storage is provided by the CO2QUALSTORE guideline (Aarnes *et al*., 2010). Its intention is to harmonise the implementation of CGS in compliance with regulations, international standards and directives while avoiding additional documentation and reporting requirements. This is fully valid also for storage site remediation, although the authors use the terms contingency, contingency plan, contingency measures, contingency monitoring, rather than remediation.

CO2QUALSTORE considers contingency and remediation planning an essential part of the risk and uncertainty management. Planned contingency measures represent one type of measures aimed at reduction of risk and associated uncertainties. In the bow-tie risk management model (Fig. 5-3), remediation and mitigation measures are part of the consequence reducing measures (right part of the diagram) that are implemented after a feature, event or process (FEP) has occurred. They can be regarded as emergency response measures. A collection of such measures should be assessed and planned in a contingency (remediation) plan. In general, such plans should provide sufficient confidence to the regulators as well as to other stakeholders, including the public, that the storage site will provide long-term storage of CO_2.

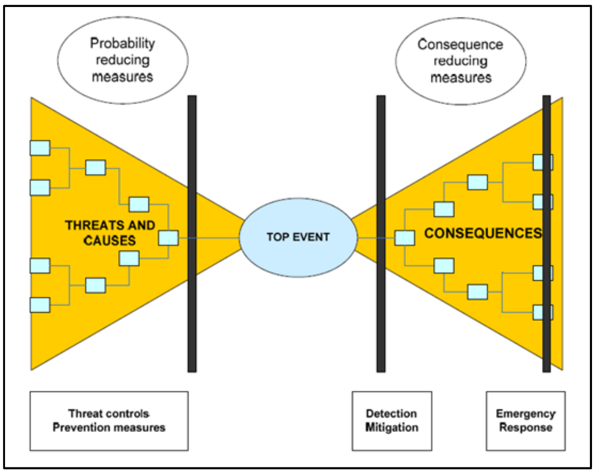

Fig. 5-3: Bow-tie risk management model according to CO2QUALSTORE (Aarnes *et al*., 2010). Mitigation and remediation are part of consequence reducing measures (right-hand part of the diagram).

The guideline suggests as a good practice that early warning signals (of an irregularity or leakage) detected by base case monitoring trigger additional contingency monitoring, aimed at acquisition of additional data that can be used, among others, to properly select and design remediation measures. The whole process represents a part of the risk-reduction procedure, as illustrated by the risk reduction triangle in Fig. 5-4.

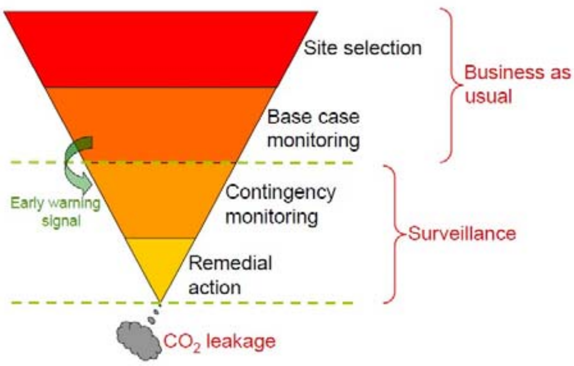

Fig. 5-4: Risk reduction triangle according to CO2QUALSTORE (Aarnes *et al*., 2010). Remediation is shown at the bottom vertex of the triangle.

CO2QUALSTORE recommends that a contingency plan is an integral part of a CO_2 development plan, the basic component of a storage permit application (Fig. 5-5). The contingency plan is defined as a plan to implement corrective measures, if a significant irregularity occurs. The corrective measures should be prioritised and ranked according to the assessed cost-effectiveness of their risk/uncertainty reducing effect. In addition, the plan should document that conceivable significant irregularities can be adequately controlled, and express the project developer's commitment to implement appropriate contingency measures, if necessary.

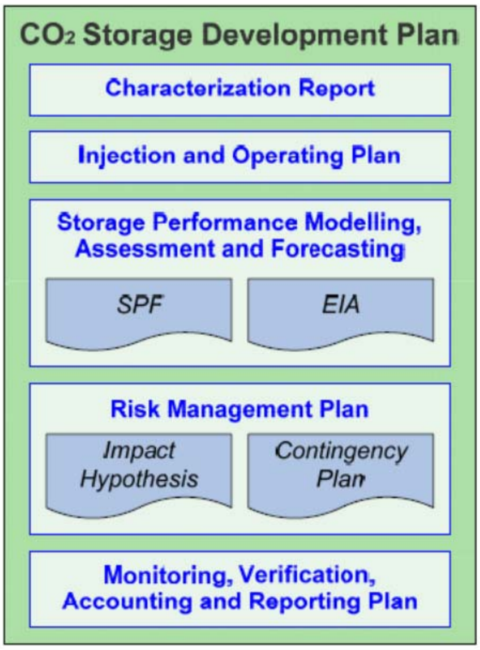

Fig. 5-5: Components of the CO_2 storage development plan according to CO2QUALSTORE (Aarnes *et al*., 2010).

Appendix B4 of CO2QUALSTORE (Aarnes *et al*., 2010) provides detailed guidelines on the preparation of the Contingency plan. The plan should be drafted together with another document – the Impact hypothesis. Both documents should be based on the conclusions of basic documents of the previous phase of storage site development procedure – the Environmental Impact Assessment (EIA) and the Storage Performance Forecast (SPF). While the impact hypothesis should focus on measures to prevent significant irregularities under normal operating conditions, the contingency plan should contain corrective measures plan for alternative scenarios (Fig. 5-6). In particular, the plan should describe how to control site performance scenarios that differ from the base case scenario during the operational lifetime of a CO_2 geological storage project, and provide assurance that these scenarios can be adequately managed. Both documents together form the project risk management plan.

The key input to the development of the contingency plan is the risk and uncertainty assessment, including the assessed effectiveness of risk/uncertainty reducing measures (safeguards), and the defined project performance targets. Therefore, the process of developing the plan should start by reviewing the results of the risk and uncertainty assessment. For each of the identified risks, a list of associated safeguards should be compiled. Moreover, a rough estimate of the costs of each safeguard should be provided in order to be able to rank the corresponding cost-effectiveness of alternative safeguards.

The contingency plan should demonstrate that the collection of safeguards provide adequate assurance that the worst-case scenarios associated with the identified risks can be adequately controlled. For this purpose, it may be useful to classify the safeguards according to their objectives. For instance, it should be demonstrated that all safeguards aiming to manage and constrain reservoir pressure together provide adequate assurance that pressure can be properly controlled.

The contingency plan should describe contingency measures for a sufficiently broad range of alternative site performance scenarios, and provide rough estimates of the associated costs.

In general, current regulatory frameworks and supporting guidelines tend to a consensus that approaches for proper site management procedures must be tailored to the unique characteristics of each site (i.e., they should be site-specific). Risk-based approaches are promoted. These approaches direct attention towards the most significant risks, as opposed to consequence based approaches that direct attention towards events with the largest consequences. This gives more flexibility in the project design to project developers, and more influence on project management to the regulators. The risk-based approaches also give an incentive to reduce risks beyond established minimal thresholds. Acceptable risk levels, accompanied by proper remediation (contingency) plans, should be defined on a case by case basis for each project through an interactive dialogue between regulators and project developers (Aarnes *et al*., 2010).

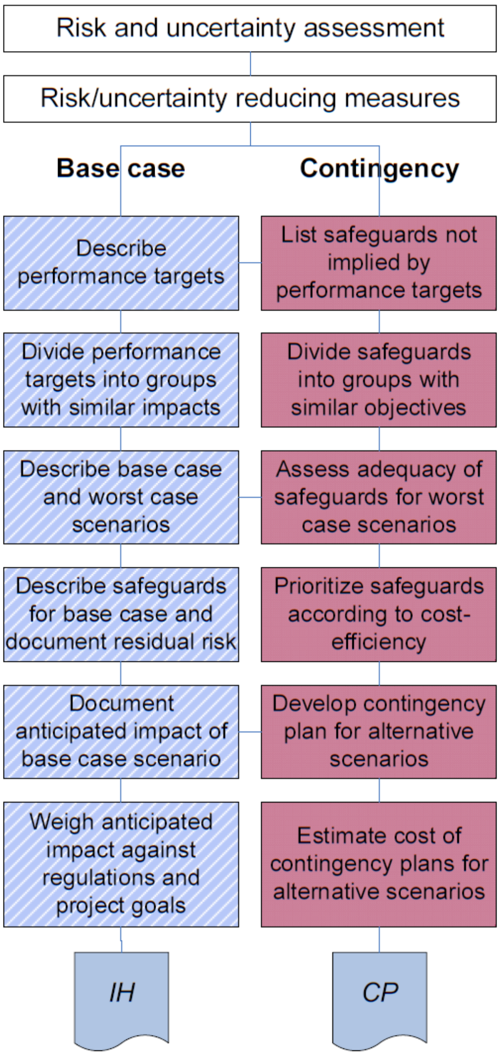

Fig. 5-6: Workflow for preparation of the Impact hypothesis (IH) and Contingency plan (CP) according to CO2QUALSTORE (Aarnes *et al*., 2010).

It also needs to be taken into account that the whole cycle of site characterisation, risk-assessment (including contingency and remediation planning) and monitoring and verification is a continuous process that extends throughout the project life-cycle. This means, among others, that all the relevant documents, including remediation (contingency) plans, should be periodically revised, according to the improved knowledge of the reservoir and its behaviour.

It is probable that a review and update of the storage permit is required during the operational phase. For instance, the EU CCS Directive (2009) requires a permit review not more than five years after issuing the permit and then after every 10 years. Moreover, a review, update or withdrawal of the storage permit can be ordered, based on subject to certain criteria, incl. a leakage or significant irregularity.

The US EPA rule (USEPA, 2010) suggest similar criteria and periods for permit review, although the injection permit is issued for the operating life of a CGS project. In case of significant irregularities, leakage, altered operation conditions, understanding that the storage integrity may be compromised or that the permit conditions may have been breached, a re-qualification of the permit is necessary.

Besides the above, other available general regulations and standards that are in broad agreement with the CO2QUALSTORE guidelines include the IEA CCS Model Regulatory Framework (IEA, 2010), the Canadian standard on CO_2 storage CSA Z741 (CSA, 2012) and the more general risk management ISO 31000 (ISO, 2009).

The next section focuses on the regulatory regimes that are in place in various parts of the world where CO_2 storage activities are on-going or likely to start in near future (Europe, USA, Canada and Australia).

5.2.1 Regulatory regime for site remediation in Europe

The EU CCS Directive (2009) and its Guidance Documents 1 and 2 (EC, 2011a, b) represent the principal regulatory regime for all EU Member States in relation to the geological storage of carbon dioxide, although additional regional and local regulations may exist in the Member States.

In terms of reasons for site remediation, the CCS Directive defines:

- Leakage: any release of CO_2 from the storage complex (storage site and surrounding geological domain, which can have an effect on overall storage integrity and security; that is, secondary storage containments).
- Significant irregularity: any irregularity in the injection or storage operations or in the condition of the storage complex itself, which implies the risk of a leakage or risk to the environment or human health.

The EU CCS Directive requires that a corrective measures plan is prepared by the operator and submitted as part of the storage permit application, which should be “ready to use” (in the sense described by Kuuskraa and Godec, 2007) immediately in case of leakage or significant irregularities. Article 16 of the CCS Directive describes the measures that should be taken in case of leakage or significant irregularities and states that Member States shall ensure:

- That in the event of leakages or significant irregularities, the operator immediately notifies the competent authority, and takes the necessary corrective measures, including measures related to the protection of human health. In cases of leakages and significant irregularities which imply the risk of leakage, the operator shall also notify the competent authority pursuant to the EU ETS Directive (2003).
- The corrective measures referred above shall be taken as a minimum on the basis of a corrective measures plan submitted to and approved by the competent authority in the application permit.
- The competent authority may at any time require the operator to take the necessary corrective measures, as well as measures related to the protection of human health. These may be additional

to or different from those laid out in the corrective measures plan. The competent authority may also at any time take corrective measures itself.

- If the operator fails to take the necessary corrective measures, these measures shall be taken by the competent authority, which shall recover the costs from the operator including by drawing on the financial security pursuant to Article19 of the EU CCS Directive.

Corrective measures are actions, measures or activities taken to correct significant irregularities or to close leakages in order to prevent or stop the release of CO_2 from the storage complex. Intended to ensure the safety and effectiveness of geological storage, corrective measures are part of the overall risk management process. They ensure the safety of geological storage and manage the risks from leakage during the project life cycle. Corrective measures, as mentioned in the Guidance Document 2 (EC, 2011b), should be:

- Risk based; linked to identified risks from site and complex characterization (and risk assessment) and subject to the limitations of available technologies;
- Specific to the storage site and complex;
- Suitable for use to address leakage or significant irregularities from identified leakage pathways and specific leakage mechanisms out of the storage complex and any leakage to the surface;
- Closely linked to monitoring plans and monitoring, which should provide triggers for use of corrective measures by identification of leakage or irregularities;
- Used when there is any leakage or significant irregularities.

Monitoring and corrective measures are closely interlinked and the plans and activities should be developed by the operator in a wholesome manner along with the risk assessment. The competent authority should seek to ensure close integration between these measures.

The deployment of corrective measures is required in the event of leakages or significant irregularities, and would usually be detected by monitoring results or inspections. In addition monitoring is used to assess the effectiveness of corrective measures. Additional monitoring activities may be required in event of any leakage or significant irregularities.

Corrective measures may be used at any stage in the life cycle after storage permit award and are expected to be used mostly during the operations (injection) phase and post-closure pre-transfer phase. After transfer of responsibility, corrective measures may still be required, although the likelihood is reduced from then on as the CO_2 plume reaches stability.

Under normal operating conditions, in the event of leakages or significant irregularities, the operator has to immediately notify the competent authority both under the EU CCS Directive (2009) and the EU ETS Directive (2003) and take the necessary corrective measures, including measures related to the protection of human health. Measures approved in the corrective measures plan shall be taken as a minimum.

Initial plans will be based on the risks identified for the storage complex, with predicted pathways and scenarios for potential leakage based on site characterization and modelling. The types of risk and pathways would likely be similar to generic types of pathways that are described in Guidance Document 1 (EC, 2011a), primarily either geological pathways (e.g. faults, fractures or caprock absence), manmade pathways (i.e. well bores or old mine workings) or the other types of risk (e.g. groundwater contamination, displaced oil and gas, subsidence). The general locations of many potential pathways can be predicted ahead of any leakage situation, e.g. the location of a major fault or a wellbore. However, some potential leakage pathways may not be detectable (e.g. sandstone intrusions) with current technologies at the time of initial risk assessment and corrective measure plans or their locations may be uncertain. If these emerge subsequently, site characterisation, risk assessment, monitoring and corrective measures plans will need to be updated as necessary.

The operator and competent authority should consider that the actual and specific location of any significant irregularity or leakage will usually not be known before it is detected, nor will the actual pathway between the leak and the surface if the flow is not direct (which may be the case as a leak may involve a complex three dimensional problem combining the geology and well pathways). The corrective measures will ultimately need to be specific to the actual leakage or significant irregularity, taking into account the precise location and nature of the leakage or irregularity, and the specific situation and circumstances in which the leak occurred. Flexibility is required to update and change the plan according to the specific situation.

Early warning and early intervention in the detection of significant irregularities will urge to take action through corrective measures to prevent the situation getting worse, and reduce the risk of actual leakage from the storage complex. In the event of a leakage or significant irregularity the operator must immediately notify the competent authority and take the necessary corrective measures, including measures related to the protection of human health. The competent authority needs to ensure the immediate implementation of correctives measures as a minimum on the basis of the presented corrective measures plan. Handling and implementing corrective measures in the event of actual leakage to surface will require rapid and effective interaction between the competent authority and operator. It will require strong technical expertise in drilling, well engineering and geosciences. Specialist consultants would often be involved in comparable situations in the oil and gas industry. competent authorities will need to know what expertise exists within their organizations and where and when to draw on external experts.

Corrective measures can be applied to two major types of pathways: (1) to the natural, geological system and (2) to the engineered, wellbore system. While technically it is feasible to implement corrective measures and repairs, in general, their effectiveness and potential to restore the geological system is considered limited. In principle, the well can be accessed, allowing tools to be run or operations to be performed in order to repair leakages or irregularities of the wellbore and its immediate surroundings. Wells actually are the only direct connection to the subsurface. Flaws in the geological system can typically be corrected only when wells are penetrating the affected zone. Nevertheless, geological anomalies may often reflect three-dimensional problems, significantly extending the vertical and/or lateral directions, rather than giving a localized problem. This reduces the number of options to repair the issue. Corrective measures involving early interventions and modifications to injection operations will usually be beneficial and can provide effective risk management in some circumstances. The Guidance Document 2 (EC, 2011b) and the Aspen Report (Arts *et al.*, 2009) summarise some of the corrective measures methods both for geological system and wells.

Managing injection rates, locations and pressures can be used to manage some of the risks relating to geological leakage pathways and risks. However, many of the other technologies for managing issues related to geological pathways are more novel and also uncertain. Technique effectiveness involving new wells that intersect with plumes or pathways will depend on being able to identify the target area, which may be difficult in a three dimensional space. Other techniques with extraction of either CO_2 or water are technically plausible but handling the produced fluids and undertaken costs will need to be evaluated on a case by case basis. We should take into consideration that:

- Any corrective measures will be highly specific and need to take account the nature, flux and location of the leakage or irregularity (in three dimensions), which may be poorly understood especially for geological pathways.
- Gathering further data through monitoring and re-evaluation of site characterization and modelling is essential.
- Corrective measures for dealing with leakage or significant irregularities from wells are generally considered feasible using techniques and practices from the oil and gas industry or gas storage.
- Managing injection rates, locations and pressures can be used to manage some of the risks relating to geological leakage pathways and risks.

- Other approaches involving extraction of CO_2 or water are possible but the fluids produced will need to be handled and the costs may be high.
- The costs of any corrective measures will be highly uncertain and specific to the leakage or irregularity being addressed.

CAs should be aware that the status of the technologies that may be used for corrective measure is highly variable. Virtually none of the technologies have yet been used in CO_2 storage applications or environments.

The EU CCS Directive requires that the corrective measures plan be based on the risk assessment. For risks identified during the risk assessment, corrective measures have to be developed and described in the corrective measures plan. Currently, such measures are available only for certain kinds of risks. In some cases, only very generic measures like reducing reservoir pressure or aborting injection are currently proposed.

The corrective measures plan has to be handed in as part of the storage permit application. Detailed corrective measures have to be developed before injection has started. It can be assumed that, in case a risk materializes, it has to be assessed, whether the foreseen corrective measure is suitable, or whether changes to the measures are needed. Over the lifetime of a storage site new corrective measures might emerge or the approach in measures might change. Furthermore, with increased experience about the storage site, risks might be considered irrelevant or new risks might. It thus seems advisable to regularly update the corrective measures plan. This could be in line with the timeframe for regular updating of the monitoring plan.

The Guidance Document 2 (EC, 2011b) and the Aspen Report (Arts *et al*., 2009) propose a possible format for the corrective measures plan aiming to enhance transparency and comparability as well as exchange of information with regards to corrective measures plan. It consists of two parts. In the first section (Tab. 5-1) an overview is given on the corrective measures to be taken for the risks identified. Threshold values or qualitative circumstances are stated, which will trigger the implementation of a corrective measure. Furthermore, the monitoring methods used to monitor the effectiveness of a corrective measure are named together with the number of the method from the monitoring plan (used for easier identification of methods throughout the plan). In the second part of the plan (Tab. 5-2), each corrective measure is described in detail with regards to the timeframe needed for implementation and the detailed activities to be carried out. Furthermore, a rationale is to be delivered, why the corrective measure is appropriate for the risk it is related to.

Tab. 5-1: Corrective measures plan section 1 - Overview of risks and measures (Guidance Document 2, EC, 2011b).

Risk the measure is related to	**Irregularity this measures is related to**	**Corrective measure**	**No. of corrective measure**	**Monitoring method (s)**	**No. of monitoring method**
Comment: Please state the risk(s) as identified in the risk assessment	Comment: Please state the threshold values or qualitative conditions which will trigger this corrective measure			Comment: Please state name and number of the monitoring method(s) used to monitor the effectiveness of the corrective measure, as stated in Table 1	
		Measure A	No. 1	Method D	No. 4
		Measure B	No. 2		

Tab. 5-2: Corrective measures plan section 2- Detailed potential corrective measures (Guidance Document 2, EC, 2011b).

Name of Corrective Measure:		Measure A
No. of corrective measure	Comment: Please state the number of the corrective measure as found in the corrective measures overview table	No 1
Estimated timeframe needed for implementation	Comment: Please state how much time the full implementation of the measures is expected to take	
Detailed description of measure	Comment: Please state on a detailed technical level, what the measure consists of: What is done where and when?	
Rationale for the use of the measure	Comment: Please state why this measure is suited for the risk it is related to	
Current status of the technique	Comment on the status of the technique or method, i.e. whether proven, commercial, under development, etc.	

5.2.2 Regulatory regimes for site remediation worldwide

International regimes

The OSPAR Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations (OSPAR, 2007) include a Framework for Risk Assessment and Management (OSPAR-FRAM, 2007). FRAM sets out a framework for assessing the risks posed by a CO_2 storage project to the marine environment. There are six stages of FRAM, the last of which ("f") focuses on risk management: including monitoring, mitigation and remediation measures. According to the Guidelines, any CO_2 storage permit or approval must contain a risk management plan that should include (among others):

- mitigation and remediation options including the pre-closure phases; and
- requirement for a site closure plan, including a description of post-closure monitoring and mitigation and remediation options.

For leakage occurring through an active or abandoned well, the OSPAR Guidelines propose the following remediation methods:

- Recapping wells or repairing faults in cement between rock and casings; and
- Drilling intersecting wells followed by controlling the leak with heavy mud followed by recapping.

If leakage occurs through faults or fractures, recommended remediation methods are:

- Lowering the injection pressure or the formation pressure by removing water or other fluids;
- Halting the injection until the project is stabilised;
- Transferring CO_2 streams to a more suitable formation; and
- Plugging the pathway by injecting sealing material.

The London Protocol parties adopted in 2012 Specific Guidelines for the Assessment of Carbon Dioxide for Disposal into Sub-seabed Geological Formations (LC, 2012) that take over many parts of the 'OSPAR FRAM' framework. In addition, a mitigation or remediation plan is separately defined. Such a plan should be in place to enable a rapid and effective response to leakage to the marine environment. Seismicity in the area, which could potentially lead to leakage, should be considered in these plans. The mitigation or remediation plan should consider the likelihood that carbon dioxide streams will migrate or leak as well as the types and magnitudes of potential effects of such migration or leakage over time. The requirements of the mitigation or remediation plan and the corresponding preventive and corrective measures are determined by national authorities on the basis of the potential impact of the migration or leakage on human health and the marine environment both in the short- and long-terms. If leakage poses a significant risk to the marine environment and cannot be controlled by any mitigation or remediation operation, injection should be ceased, or be modified, or the CO_2 may be transferred to a more suitable location depending upon site-specific factors.

The IEA model regulatory framework (IEA, 2010) also uses the 'OSPAR FRAM' as one of the most important input materials. The OSPAR-FRAM chapter 6.8 provides a description, explanation and model text of regulation on corrective and remediation measures. According to the report, it is important that regulatory frameworks for CO_2 storage ensure that any significant leakage, unintended migration or other irregularity in storage site operations are corrected in a timely manner and that any damages are remediated. CO_2 regulatory frameworks should stipulate both the entity that is to be financially liable for corrective measures and remediation measures and the entity required to perform those measures.

USA

The USEPA regulations, namely the Federal Requirements Under the Underground Injection Control Program for Carbon Dioxide Geologic Sequestration Wells (USEPA, 2010), require that the storage site owner or operator must develop and maintain an emergency and remedial response plan that describes actions to be taken to address events that may cause endangerment to underground sources of drinking water (USDW) during the construction, operation, and post-injection periods of the project. The plan should describe measures that would be taken in the event of adverse conditions at the well, such as a loss of mechanical integrity, the opening of faults or fractures within the area, or if movement of injection or formation fluids caused an endangerment to a USDW.

The plan should be site-specific and risk-based. Response in case of failure should be made through consultation between owners or operators and the Director (the person responsible for permitting, implementation, and compliance of the Underground Injection Control /UIC/ program) because each response action will be site and event specific. If an owner or operator obtains evidence of endangerment to a USDW, he or she must:

- immediately cease injection;
- take all steps reasonably necessary to identify and characterise any release;
- notify the Director within 24 hours; and,
- implement the approved emergency and remedial response plan.

Owners or operators must also periodically update the emergency and remedial response plan to incorporate changes to the area or other significant changes to the project.

The World Resources Institute provides Guidelines for Carbon Dioxide Capture, Transport, and Storage (WRI, 2008) where mitigation or remediation planning is an integral part of Storage Guideline 1: Recommended Guidelines for MMV. Remediation options need to be associated to every possible risk scenario. At the same time, risk assessments should provide the basis for mitigation/remediation plans for response to unexpected events; such plans should be developed and submitted to the regulator in support of the proposed MMV plan. The guidelines provide a nice overview of possible mitigation and remediation measures that can be applied in response to typical risk scenarios that appear in the risk assessment process of a CO_2 storage project (see Tab. 5-3).

In addition to the Federal level of rules and guidelines, there are individual state regulations (e.g. Louisiana, Texas, Wyoming, etc.) that, however, usually do not include detailed provisions regarding remediation measures, except well plugging.

Tab. 5-3: Mitigation/remediation options associated with typical risk scenarios of a CO2 storage project (WRI, 2008).

Risk Scenario	Mitigation/Remediation Options
Leakage through faults, fractures and spill points	■ Shut off valves to stop injection. ■ Lower injection rates/pressure. ■ Lower reservoir pressure by removing water or other fluids from the storage reservoir. ■ Create a hydraulic barrier by increasing reservoir pressure upstream of the leak. ■ Install chemical sealant barriers to block leaks (Jarrel et al. 2002). ■ Stop injection, extract CO_2 from storage reservoir, and re-inject it into a more suitable reservoir.
Leakage through active or abandoned wells	■ Repair leaking wells by replugging with cement. ■ Repair leaking injection wells with standard well recompletion techniques, such as replacing the injection tubing and packers. ■ Plug and abandon wells that cannot be repaired. ■ Create a hydraulic barrier by increasing reservoir pressure upstream of the leak. ■ Install chemical sealant barriers to block leaks. ■ Stop injection.
Leakage into the vadose zone and accumulation in soil	■ Extract CO_2 from the vadose zone and soil gas by standard vapor extraction techniques. ■ Pump CO_2 away from trenches or other low-lying areas, and either vent or reinject it in the subsurface. ■ Employ passive remediation, such as diffusion and barometric pumping to slowly deplete one-time releases of CO_2 into the vadose zone. This method may not be effective for managing ongoing releases, because it is relatively slow. ■ Irrigation and drainage or alkaline supplements (such as lime) can be used to remediate soils that have acidified because of CO_2 exposure. ■ Create a hydraulic barrier by increasing reservoir pressure upstream of the leak. ■ Install chemical sealant barriers to block leaks. ■ Stop injection.
Accumulation of CO_2 in groundwater	■ Drill wells that intersect the accumulations in groundwater, and use them to extract the CO_2, either in pure form or dissolved in groundwater. ■ Dissolve mineralized CO_2 in water, and extract it as a dissolved phase through a groundwater extraction well. ■ Pump CO_2-contaminated groundwater to the surface, and aerate it to remove the CO_2. For possible trace element contamination, "pump-and-treat" methods can be used. ■ Create hydraulic barriers to immobilize and contain any contaminants by appropriately placed injection and extraction wells. ■ Employ passive methods that rely on natural biogeochemical processes. ■ Create a hydraulic barrier by increasing reservoir pressure upstream of the leak. ■ Install chemical sealant barriers to block leaks. ■ Stop injection.
Accumulation of CO_2 in indoor environments with chronic low level leakage	■ Manage potential slow indoor releases with basement/substructure venting or pressurization. Both would have the effect of moving soil gases away from the indoor environment. ■ Create a hydraulic barrier by increasing reservoir pressure upstream of the leak. ■ Stop injection. ■ Use fans to disperse CO_2, similar to radon fans.
Accumulation in surface water	■ Shallow surface water bodies that have significant turnover (shallow lakes) or turbulence (streams) will quickly release dissolved CO_2 back into the atmosphere. ■ Do not locate projects near deep, stably stratified lakes; however, if impacted, active systems for venting gas accumulations in these lakes have been developed and applied at Lakes Nyos and Monoun in Cameroon. ■ Create a hydraulic barrier by increasing reservoir pressure upstream of the leak. ■ Install chemical sealant barriers to block leaks. ■ Stop injection.
Large releases of CO_2 to the atmosphere	■ Use large fans to rapidly dilute CO_2 to safe levels for releases inside a building or confined space. ■ Dilution from natural atmospheric mixing (wind) will rapidly dilute CO_2 from outdoor releases over a large area in many cases. ■ Install chemical sealant barriers to block leaks. ■ Stop injection.

Canada

In Canada, the regulations predominantly fall under provincial jurisdiction. The provinces of Alberta and Saskatchewan have the most advanced regulatory frameworks. CO_2 storage is usually handled in the framework of other activities (acid gas disposal, EOR) and no detailed requirements for remediation measures related specially to CCS are specified.

Australia

The Offshore Petroleum and Greenhouse Gas Storage Act (OPA, 2013) defines the term “serious situation”, which in fact combines the terms “significant irregularity” and “leakage” according to the EU CCS Directive. In case of a “serious situation”, the responsible Commonwealth Minister may direct the licensee, among others, to cease or suspend injection operations and undertake remediating activities. The Minister possesses considerable power and responsibility in such situations, which are properly described in the Act.

While the OPA act deals with Australian offshore, the onshore activities are covered by legislation of individual states, which mostly mirrors the Commonwealth acts. Usually, no detailed provisions regarding site remediation are provided.

5.3 Conclusions

Remediation measures are an integral part of regulatory regimes for CCS in all relevant countries and regions where CCS activities are on-going or planned. The comparison shows that most of the regimes are based on similar foundations, closely linking risk assessment, monitoring and remediation measures into one mutually interconnected package. The European and U.S. legislations appear to be the most detailed and most elaborated.

As far as remediation measures are concerned, these can be divided into three categories. The first part, corresponding mainly to wells and well intervention techniques, can be based on proven practice of the oil and gas industry. The measures can be used, with or without minor modifications, at CO_2 storage sites as well. The second group represents techniques that are common in hydrogeology and pollution control. Here, the technology is either limited to shallow subsurface, i.e., to remediation of CO_2 leakages up to the uppermost parts of the geological profile, or, the techniques need to be used in greater depths, beyond their usual depth limits.

The final group of techniques are the newly developed ones, directed specially at CO_2 storage sites. This group includes, e.g. special materials (special cements, self-healing substances, etc.) or special aquifer management techniques. Due to the fact that remediation techniques for CCS are subject of intensive on-going research and development, further improvements of existing and introduction of new methods and technologies can be expected in the near future.

6 DIRECTIVES AND REGULATIONS RELATED TO STORAGE SITE CLOSURE AND POST CLOSURE

This chapter provides an overview on the methods and the regulatory requirements for CO_2 injection sites over the period of closure and post closure. It is structured chronologically, starting with the process of abandoning the injection wells and concludes with an overview of how the liability for the project site can be transferred to the relevant authorities.

The first part briefly discusses the different regulations concerning CO_2 site closure, which are still under development (especially the national directives). The chapter also provides information on already existing requirements for well abandonment in the hydrocarbon industry, using international conventions as well as accessible regulatory data from countries engaged in oil and gas production. The regulations for decommissioning of oil and gas production operations have already served as a general basis for developing guidelines concerning the handling of CO_2 sites because of the similarity of the subject.

Among the activities conducted during site abandonment, well abandonment is considered the most important process, as it should prevent all physical hazard induced by the well, prevent any migration of contaminants and ensure that no communication between originally separated hydrological systems is occurring. Therefore, the chapter also provides a brief overview on the potentially required technical details (plug placement) as well as overall objectives of proper well abandonment (preserve hydrogeological systems).

Following well abandonment, the post-closure phase is described, starting with a brief discussion on how to prove the safety of stored CO_2. After summarising the iterative process of characterisation of the reservoir, the general requirements for long-term storage safety, certain modelling techniques, risk management and suitable monitoring options are discussed. As all monitoring plans must be chosen according to the particular risks of the project, a variety of monitoring options also are presented.

The last step in the post-closure phase is represented by the transfer of liability. Exemplary regulations, like the EU Guidance Documents are discussed briefly.

Generally the phase of closure and post-closure is the part of the CCS life-cycle that has been practised the least, which leaves room for developments and discussion, especially concerning the final step of transferring the responsibility of the site.

The following sections provide an overview on the methods and the regulatory requirements for CO_2 injection sites over the period of closure and post closure. Primarily based on the “Report on the international regulatory requirements on CO_2 geological storage and site abandonment” (Korre, 2011) and the “D1.2 Report on the current site abandonment methodologies in relevant industries” (Wollenweber, 2012) by the project CO_2Care - CO_2 Site Closure Assessment Research the objective is to summarise and provide updates on international, EU and national directives as well as guidelines for abandonment methodologies.

Site abandonment is generally defined as any actions taken by the operator to close down a previously operating field. The regulations concerning CO_2 site closure are, especially the national directives, still in a stage of development. That is why additionally the chapter gives information on the already existing requirements for well abandonment in the hydrocarbon industry, which due to the similarity of the subject already served as basis for guidelines concerning the handling of CO_2 sites. Also many CCS projects will need to know the conditions of existing/abandoned oil and gas wells to decide if they are suitable for use in CO_2 storage.

Concerning CO_2 site closure there are a few terms which are frequently used but have slightly varying meanings for the different regulations in use.

Generally in the UK and the EU, the term “closure” defines the moment of cessation of CO_2 injection. Internationally the US UIC (Underground Injection Control) and IEA (International Energy Agency) speak of closure when the operator is released from site care. IEA mentions additionally a “closure period” which defines the time between cessation of injection and the point when the operator is no longer responsible for the site. Abandonment defines the general process required when the well is no longer in use. “Post closure” is the period after the end of injection. Different protocols provided by IEA (International Energy Agency), IOGCC (Interstate Oil and Gas Compact Commission) and WRI (World Resources Institute) define “post closure” as the period after a certification of closure (by the appropriate authority). This certification may also contain the release of the operator and the “transfer of liability”, which defines the moment when site care is transferred to the authorities or when the authority certifies that the site is safe.

6.1 Well abandonment, site closure procedures and regulations

Among the activities included in proper site abandonment, well abandonment is considered the most important process. Typically it should prevent all physical hazard induced by the well, prevent any migration of contaminants and prevent communication between originally separated hydrological systems. There are a lot of regulatory requirements on the subject of well abandonment on an international, European-wide and national level.

The main international regulations are the “London Convention and London Protocol”, dealing with international treaties and the limitation on discharge of land based waste at sea, and the “OSPAR Decision 2007/2 and Agreement 2007-12” on regulations and protection of the marine environment. Additionally there is also a model regulatory framework by the International Energy Agency (IEA).

Concerning regulations within the European Union the main documents on the subject are the EU Directive 2009/31/EC from 25/6/2009 with regulations for permitting CO_2 storage and accompanying Guidance Documents and the EU CCS Directives with relevance for CO_2 storage 2003/87/EC, 2009/29/EC and 2010/245/EU.

National regulations on well abandonment are country specific but with similar details. In the European Union either the national regulations are based on the transposition of the EU Directive 2009/31/EC (like in Spain where the CCS Act 40/2010, which is a full transposition of the EU directive, entered into force on 31.12.2010), or it is based on amendments of already existing subsoil regulations (for example Denmark)

6.1.1 Relevant regulations from the hydrocarbon industry (oil and gas production)

Well abandonment is typically handled by national policies and procedures - therefore there is a wide range of legal directives worldwide. To provide an overview about regulations concerning well abandonment in the hydrocarbon industry the accessible regulatory data from countries significantly engaged in oil and gas production as well as international conventions were taken into account. The technical study on “Long Term Integrity of CO_2 Storage – Well Abandonment” by the IEA Greenhouse Gas R&D Programme 2009 provides a lot of detailed information on abandonment regulations of the hydrocarbon industries to lead to a best practice abandonment strategy for CO_2-Storage wells.

Denmark

The Danish subsoil act (L141, 2011, the Danish Parliament) serves as a basic framework for petroleum exploration and recovery. It deals in general terms of action, which leaves room for adaptations and detailed regulations. However, it regulates the exploitation and recovery activities of minerals and especially hydrocarbons in the Danish subsoil and continental shelf.

Since 2007 “A Guide to Hydrocarbon Licenses in Denmark” provides guidelines for drilling-exploration and information on well abandonment. In general the document states that exploration wells shall be plugged in such a way that no fluid flow through the hole and no communication from down-hole to surface via casing-annulus are possible. Therefore multiple plugs have to be placed. The weight of the plugs has to be sufficient to ensure that the system is in pressure balance. In uncased boreholes the plug should at least extend to 50m below and above the permeable zones, in open hole parts below the cased wells the plug should cover the interval from at least 50m above and below the casing shoe. Additionally another cement plug at 50m on top is required.

Any perforated intervals is to be isolated, cemented and plugged 50 m below and above the permeable interval. Also all plugs shall be pressure tested for a sufficient time to detect possible leakage of mechanical failure, the top cement plugs shall be located by load testing.

France

The Ministry of Economics, Industry and Employment provides the “Règlement Général des industries extractives”, which was revised in the year 2000 and contains articles on closure and abandonment of wells (“fermeture définitive du puits”) focusing on onshore and offshore well abandonment. The steps required are dependent on age and state of the wells, provided there is information on primary cementing and casing available. If there is no prior knowledge about the casing status, investigations are required followed by possible placing, extending and improving the cementing.

Precaution to isolate the reservoirs from each other is the primary requirement stated in the guidelines. Also the permeable layers have to remain permeable and there should not occur any mixing of fluids between different layers. Plugs with a length of at least 50m (or 100m, depending on the well bore) shall be placed according to the requirements.

Norway

In Norway any decommissioning is regulated by the 1996 “Norwegian Petroleum Activities Act” and the OSPAR Convention. In general the petroleum act requires a decommissioning plan two to five years prior to expiration of the license or termination of facility, submitted by the licensees. The decommissioning plans have to contain a disposal plan as well as an impact assessment.

The exhaustive and often referred to NORSOK Standard D-010, revised in June 2013, provides specific abandonment regulations, focusing well integrity. The primary objective is that permanently plugged wells shall be abandoned with eternal perspective. That means that NORSOK Standard D-010 requires at least one barrier between surface and potential inflow, hydrocarbon reservoirs require two well barriers. The plug lengths of 100 m should extend at least 50 m above the potential inflow-source, the plug of open hole wells shall be placed at minimum 50 m below the casing shoe. Any installations have to be verified through documentation of job performance, the position of plugs by pressure tests or tagging.

Netherlands

In 2003 a new updated mining act containing rules for exploration and development of mineral resources and mining activities was released. More technical details on well abandonment are found in the mining regulations. They state specific requirements like an additional primary cement sheath outside of the casing to well plugs and a working program to document the cementing per casing interval. Also there are extensive regulations for plug placement and uphold safety requirements, whereas little technical attention is paid on down-hole primary well cementation.

UK

The Petroleum Act entered into force in 1998. Decommissioning of onshore wells and associated hydrocarbon installations requires permission from the Department of Trade and Industry, offshore-wells need accordance with the Oil & Gas UK Guidelines for the suspension and abandonment of Wells (by UK Offshore Operations Association UKOOA). There the main characteristics of plugging material, the location of plugs for proper isolation from the surface and verification procedures for an acceptable permanent barrier are noted. In general the primary barrier characteristics required are low permeability, long-term integrity, no shrinking and non-brittle materials, which will be bonding to casing and resistant to down-hole fluids.

Two permanent barriers from surface are required to ensure an effective isolation of the hydrocarbon reservoirs. The first barrier should be placed at least 100 ft above the potential in-flow, the second barrier will serve as backup for the first one. The position and effectiveness of barriers needs to be confirmed. There are no specific requirements on the verification-process stated, but recommend minimum requirements are mentioned.

Australia

In Australia the main operations of the hydrocarbon industries are situated offshore (about 96 %), which are regulated by the Offshore Petroleum and Greenhouse Gas Storage Act 2006 as well as the Environment Protection (Sea Dumping) Act 1981. Any decommissioning is based on international protocols and treaties. There is no extensive experience on upstream petroleum decommissioning available in Australia.

Canada, Alberta

In Canada the specific policies and procedures for well abandonment are dictated by the authority of the province. In Alberta there are different abandonment programs concerning open-hole wells in oil sands for four defined areas. Generally it states that cements must be placed in a way that inhibits any cross-flow between porous zones and all non-saline groundwater has to be covered by cement. Plugs have to be extending at least 15 m above and below the isolated interval. At depths greater than 1500 m a minimum plug length of 60 m is required, for depth less than 1500 a plug of at least 30 m is considered sufficient. There is no minimum distance between plugs stated and one plug may cover several porous zones. However, the placement of plugs must be verified by an approved method.

Abandonment practices for cased-hole wells depend on the geographical location, if it was completed, and whether the well penetrated any oil sand zones. Have no oil sand zones been met, non-perforated wells do not require any additional cement plugs. Wells with oil sand intervals require separate abandonment for each completed pool and additionally all non-saline groundwater has to be covered with cement (same as in open hole). A cement plug with at least 30m length should be extending not less than 15 m below and above the liner top. Also the cement of the casing has to be in a certain required condition (Directive 009 ERCB 1990).

USA

The Regulations in USA have a distinct regional nature. However, the objective of plugging is the same in all states – primarily the protection of potable water aquifers and the isolation of hydrocarbon reservoirs. Technical details like the length of the plugs and required additives may differ from state to state. Underground Injection Control (UIC) Agency was established under the Safe Drinking Water Act (SDWA, 1974). UIC regulates at regional level the construction, operation, permitting and closure of injection wells that inject fluids in underground reservoirs. Additionally the Environmental Protection Agency (EPA) sets standards for drinking water quality. UIC defined 5 classes of wells related to the injected fluids, which require different abandonment techniques respective used material, casing condition and hydrogeological setting.

The objectives of abandonment being in general:

- Eliminate physical hazard;
- Prevent underground water contamination;
- Conserve water yield and hydrostatic head;
- Prevent intermixing of subsurface water.

The EPA regulations demand demonstration of mechanical integrity of the well before commencing abandonment. Also the mechanical integrity of the casing needs to be demonstrated before plugging. EPA states as first priority the prevention of fluid movement from the injection zone to any drinking water aquifer. Injection zone therefore require a mechanical plug with a cemented plug on top (minimum length of either 76m or 15m, depending on the used mechanical plug). Cut casing requires at least 30m cement plugging, which extends from at least 15m below to 15m above the rip point. Cement plugs must be placed at least 50m below the lowest drinking water aquifer and should ensure that no cross-flow is occurring. Any surface casing shall be cut off and the original state of the area should be restored.

API (American Petroleum Institute) provides environmentally-sound abandonment practices for oil and gas exploration, focused on onshore. API states that several safeguards, already utilized during well construction (like surface casing, production casing adequately cemented) and plugging operations (cement plugs in open holes, plugs above perforated intervals, at cut casing zones, at the base of lowermost fresh water aquifer, across surface casing shoe and at surface), help to ensure the prevention of fluid migration in abandoned wells. Cement and mechanical plugs located at critical points in the wellbore prevent fluid migration. Cement plugs should at least have a length of 30 m and extend to a minimum of 15 m above the isolating part. Perforated zones require the displacement method for plugging (cement is squeezed in or using a permanent bridge plug), with a subsequent location verification by tagging and pressure testing.

International

London Convention 1972 and 1996 Protocol is dealing with the prevention of marine pollution by dumping of wastes and other matter (in the North Sea and North-East Atlantic). The Amendment to the 1996 Protocol allows captured CO_2 to be stored into sub-seabed formations (within certain restrictions). The Protocol to the convention entered into force 2006, amendment forms basis in international law to regulate CO_2 storage offshore.

The OSPAR Convention is dealing with waste disposal and other activities in geological reservoirs under the seabed (in the Northeast-Atlantic). Although the OSPAR convention represents one of the most comprehensive and strict legal frameworks concerning protection of the marine environment, no specific regulation for abandonment of wells is included.

6.1.2 CO_2 Storage

Directives and regulations on closure and post-closure for CO_2-storage are still in development. Therefore there are only a few regulations dealing with the abandonment of CO_2-storage wells, which are mostly amendments and further recommendations of the already existing subsoil acts and directives concerning hydrocarbon exploration wells (due to the similarities of the topic).

International Regulations

The IEA Carbon Capture and Storage: Model Regulatory Framework requires for the abandonment of CO_2 storage wells a description of the location, the condition of the wells, applied plugging procedures and integrity testing results for every possibly effected well. Also a description of the decommissioning, as required by the relevant authority, is wanted.

The OSPAR and London Convention amendments related to CO_2-storage well abandonment state: "Particular attention should be paid to integrity of the wells. Over the longer term, the risk assessment should also address any change in the integrity of the seal and of the plugs in the abandoned wells and might include the effects of CO_2 dissolution and mineralization". "Special care should be taken to use sealing plugs and cement that are resistant to degradation from carbonic acid" (London Protocol, 2006b). In 2007 the OSPAR Convention made amendments for environmentally safe storage of CO_2 where they excluded the injection of CO_2 in the water column and the disposal onto the seabed.

European regulations

EU directive 2009/31/EC notes as a requirement that "the site has been sealed and injection facilities have been removed". Guidance Document 3 (EC, 2011c) mentions the necessity of appropriate materials and practices without any further details on procedure or plugging.

The SINTEF Petroleum Research Report on "Ensuring well integrity in connection with CO_2 injection" (Randhol *et al*., 2007) stated that NORSOK D-010 standard could fundamentally serve as basis for setting guidelines for CO_2 storage wells. However, it criticised some topics in NORSOK D-010 standard in relation to CO_2 applications: mainly: (1) material selection of barriers are too general and specific details missing (type of cement etc.), (2) well barriers: no plug placed in cap rock – insufficient for wells exposed to co2, (3) completion string: NORSOK leaves tubing in place also for abandoned wells – inadequate for CO_2 applications, (4) temporary well abandonment: no time frame defined, (5) monitoring guidelines missing for permanently abandoned wells

Germany

In 2012 the EU Directive 2009/31/EG was implemented in Germany as the Federal Law regarding the Application of CCS in Germany ("Demonstration der dauerhaften Speicherung von Kohlenstoffdioxid (Kohlendioxid-Speicherungsgesetz – KSpG). Before the abandonment of CO_2-storage wells it is required to submit a decommissioning plan including a description of the steps taken to prevent any leakage as well as a post-closure plan with monitoring concepts updated every 5 years. These updates lead to renewed assessment of long-term safety as well as risk and ensure an up-to-date technical maintenance. The operator has the duty to provide financial security to the authority. He will be able to transfer the liability of the storage site to the competent authority at earliest 40 years after decommissioning.

USA

EPA UIC regulations state that before placing plugs the well has to be flushed with a buffer fluid and the operator has to determine bottom reservoir pressure and perform mechanical integrity test. A plugging plan, which has to contain a bottom hole reservoir pressure test, mechanical integrity test and number and material of plugs, as well as placement of the plugs and which method was used needs an approval by the authority. There are no specifications on required materials or required tests, as they want to acknowledge the variety of available/appropriate methods and materials. The only state requirement is the compatibility of plugs with injectate to eliminate potential degradation of plugs over time.

IOGCC guide regulations state that the operator needs an approval before the plugging of wells. It also states: "Well-casing shall be cut off at a depth of 5ft below surface and a steel plate shall be welded on top identifying well name and that it was used for CO_2 injection". After well plugging, the surface installations must be removed and the site restored to its original state as far as possible.

Australia

The Offshore Petroleum Amendment requires the operator to remove all property brought to the site and to demonstrate to the Minister the removal and plugging of wells in a way that minimises quality damage to the petroleum bearing formations and maintains the suitability for permanent storage of greenhouse gas substances.

The "Queensland Greenhouse Gas Storage Regulation 2010" further requires a report when decommissioning CO_2 storage wells, which must include:

- Details on the installed well equipment with diagrams showing their dimensions and features;
- Full description of equipment that may cause a hazard to underground mining operations;
- Surveyed location of any prescribed equipment;
- Method of the cementing operations (location and type of plugs, plugging intervals, volume/type of cement, occurrences while cementing (cement loss and remediation));
- Description of any other performed abandonment procedures;
- Details of activities performed on the well to assess potential risks to safe and efficient underground mining.

6.2 Proving the safety of CO_2 site post closure

There are several abandonment steps covering this time-interval of the CCS methodology, which starts with the cessation of the injection. The steps are mostly based on a post-injection plan, which may be already required during the project application and can serve as an overview on the necessary tasks, according to the regulations.

The requirements to prove the safety of a CO_2 storage site, such as the demonstration of long-term safety, certain modelling techniques, risk management and suitable monitoring options will be discussed in this section.

The two most important factors for proving the safe containment of CO_2 in a reservoir are that there are no environmental problems occurring and that the integrity of the wells in the reservoir area is provided. Extra significant data for risk assessment are any pressure differences, the loss of injectivity, the CO_2 plume behaviour and that no leakage is detectable.

6.2.1 Modelling and risk assessment

Already during the application of a storage project it is necessary to provide evidence that at the selected project site CO_2 storage can be performed safely. Therefore a site-characterization is necessary. The characterization of the reservoir and the site is an iterative process, which consists of the following major elements:

- Data acquisition, monitoring;
- Geological model;
- Dynamic modelling;
- Risk assessment.

The geological model is based on the acquired data. The main parameters of the geological model are the model area, the geometry, grid size, possible migration pathways within the model area, faults and other tectonic attributes. Due to constant monitoring of the site more data becomes available so the geological model can be adapted and reaches more realistic values.

The static geological model is then used to perform dynamic models in order to predict the behaviour of the reservoir once CO_2 is injected. The dynamic model uses a flow model (based on the geometry characteristics of the geological model) to estimate the size of the plume, possible trapping mechanisms and the displacement of any other fluids present in the reservoir. It will further use coupled models to take into account geochemical and geo-mechanical changes in the storage formation, like pressure and stress. The results of different short-/long-term scenarios of the dynamic models are then compared to identify the site-specific uncertainties.

There is always an interaction between the 3 main players, geological model – dynamic model – risk assessment.

In general risk assessment is most effective prior to or at early stages of injection because the risks decrease with time after cessation of injection. This is not always true due to geochemical effects that may be slow and therefore will reach high risk at some point during post-closure or due to slow migration of the plume which may lead the plume into the vicinity of a leaky wells or open faults. Also tectonic activity could cause breaching of physical traps, which is dangerous if CO_2 is still in a mobile stage. So geochemistry and migration should be a part in any long-term stability evaluation for risk assessment.

If the monitored CO_2 plume is not behaving like in the predicted model the used geological and dynamical model require adjustments. The comparison stops as soon as a confident model is developed which agrees with the monitored data. Risk assessment in general is based on the geological settings and should basically answer the following considerations: How likely is leakage? How likely is leakage due to faults, wells and fractures of the reservoir? What size of leakage (leakage rate) is possible? Is there potential geo-mechanical failure, and if yes what kind? Which are the critical parameters for this site? Where to best install monitoring? Is there an environmental impact on the surrounding area? Are there any negative influences on population living in the vicinity?

International regulations

The "OSPAR FRAM" guidelines for risk assessment for CO_2 storage in the marine environment are very prescriptive and serve as model for performing risk assessment. The "Report on the international regulatory requirements" (Korre, 2011) states that: "Decision 2007/2 of the OSPAR parties requires use of the FRAM when issuing storage permits". Also the London Protocol is accompanied by specific guidelines requiring use of OSPAR FRAM and especially many elements for assessing risks like migration, leakage pathways and potential effects on the marine environment.

The OSPAR FRAM is based on six stages reaching from problem formulation and storage-site characterization via the assessment of the site response when exposed to CO_2 injection to risk characterization and management, including monitoring and remediation measures.

The IEA model framework uses OSPAR FRAM as a basis for their regulations as well.

European regulations

Modelling guidelines in the EU CCS Directive 2009/31/EC are only prescriptive in respect to the required outcomes .No particular tool is mentioned for modelling and there are no details on the level of accuracy. These guidelines are the optimum for a regulatory situation. They prescribe standards but they leave room for updated technology and practice. Risk assessment regulations in the European Union are based on OSPAR FRAM.

USA regulations

UIC regulations state that no effect on underground sources of drinking water shall occur. Furthermore they require computational modelling with respect to the extent of the plume and formation fluid (taking into account all properties of all phases of CO_2) and any migration through faults, fractures and artificial penetrations. They require extra detailed computational multiphase flow modelling, accounting for geological heterogeneities and risk assessment for leakage. All the modelling should be updated periodically or whenever irregularities occur.

The World Resources Institute (WRI) provides guidelines on what risk assessment should achieve and lists assessment points. The main concerns are leakage, the fluids potential impact on confining zones and any possible endangerment to humans and environment. WRI asks for risk assessment to identify monitoring requirements and provide the basis for mitigation. The guidelines require periodic updating and are site-specific.

6.2.2 Monitoring

Monitoring information is very relevant for providing an overview on the operational history of a site and therefore to evaluate its impact on well abandonment. Particularly real data on pressure, chemistry and plume behaviour are essential for any risk assessment of the storage area and penetrating wells. Therefore, an appropriate risk-based monitoring plan is already required as part of any site authorisation. The proposed monitoring plans will be reassessed based on available models and monitoring data during the injection phase and an adapted post-injection monitoring plan will need to be resubmitted to the relevant authority. Because there are a many different storage-sites, the requirements on monitoring plans should always be site-specific. However, to achieve at least some consistency the regulations should state objectives and performance standards rather than specific techniques to be applied. This allows for new techniques to be applied.

In General, considering EU CCS Directive 2009/31/EC and WRI Guidelines, the monitoring plan should consider:

- Site specificity, plans to take site characteristics into account.
- Monitoring plans according to site characterisation and risk assessment. High risk areas would require more heavily monitoring.
- sufficient extension of monitoring area (cover plume and surrounding environment)
- preventive/corrective measures (monitoring to ensure their effectiveness)
- best practice technology, flexibility to keep up with advancing technologies
- required frequency for the defined technique and regular/routine reporting and interpretation of data
- Flexibility, update monitoring according to changes in risks, technology, etc.
- Baseline monitoring to make inferences with monitoring
- Possible change in monitoring frequency after cessation of injection
- Possible monitoring for the time after the liability-transfer. Liability transfer demands the demonstration of site safety, but maybe low level monitoring should be considered to confirm this.

There is a wide range of monitoring options respective parameters to be monitored according to the decided site-technique. A short guide is taken from CO_2Care D 1.2 (Wollenweber, 2012) and lists the following:

1. Injection well parameters:
   - Injection rate
   - Pressure and temperature at well head
   - Chemical analysis of injected material
   - Volume of injected CO_2
   - Formation pressure and temperature
2. Well performance and integrity
   - Mechanical integrity
   - Corrosion monitoring of well
3. Pressure fall of testing. Designed to determine if reservoir pressures are tracking predicted pressures and modelling inputs
4. Monitoring well parameters (confining zone and above)
   - Pressure and temperature data
   - CO_2 saturation
   - Geochemical data
5. Geophysical images of the plume
   - Seismic
   - Electrical surveys
   - Microgravity
6. Surface deformation -> information on CO_2 plume
7. Surface detection
   - Groundwater samples
   - Soil-gas surveys

All monitoring plans must be chosen according to the particular risks of the project. The decision on spatial/temporal monitoring frequency for satisfactory results should of course be site-specific. Seismic monitoring surveys are cost intensive, but should provide at least the cover of the CO_2 plume. The number and position of monitoring wells and surface monitoring station should be based on the individual risk assessment of the project and is therefore within the responsibility of the authorities. Indirect methods used for monitoring require adequate knowledge about the relation between measured quantity and CO_2. The main factor for deciding on monitoring techniques is the cost/benefit ratio. Low cost – high benefit monitoring will definitely be used, whereas high cost - low benefit tools are unlikely to be used unless they are considered vital.

6.2.3 Demonstrating the safety of stored CO_2

To demonstrate the safety of CO_2 a huge variety of different information can be used, but the main condition being conformity of the monitored data with the predicted models. The EU Guidance Document states that conformity with the model for at least 5 years before transfer of the liability is required. It is also mentioned that the predictions for well pressure, location of the CO_2 plume, chemical composition, geochemical changes and surface deformations should lay within a specified uncertainty range, which is defined by the relevant authority.

However, there are different definitions on leakage. The EU CCS Directive 2009/31/EC states that leakage is the "release of CO_2 from the storage complex including secondary containment formations". The WRI guidelines define leakage as any significant movement of CO_2 outside the confining zone. In the OPA Bill already CO_2 migrating outside the defined migration path is considered leakage. In general the definition of the IEA CCS model regulatory framework can be used, where leakage is defined as the unintended release of CO_2 from the storage complex into the atmosphere.

Methods to demonstrate the safety of stored CO_2 can be any well monitoring of pressure and geochemistry data in the permeable layer above the confining zone, geophysical imaging of the plume and any surface detection-installations like soil-gas monitoring.

The major factor of post closure is still that the system should show stable conditions or at least be evolving towards long-term stability. For these requirements there are different indicators:

- The rate of change of the key parameters is small or declining; simulations for some thousand years and the requirements for the rate of change of the key parameters is within x%;
- CO_2 is permanently contained. The pressure is lower than the fracturing pressure, geochemistry monitoring and modelling indicate no danger and there is no well corrosion;
- There is no indication of fault-fracture opening due to micro-seismic events or injection pressure;
- Injection without any problems.

The requirement of complete stability of the CO_2 plume may be over restrictive as the plume can move horizontally at a slow rate without posing any danger. Also the plume may migrate vertically through a non-conventional seal interval over a large time-scale and the CO_2 may be dissolved or be lost as residual gas. Another possibility may be that the plume is trapped by buoyancy and slowly dissolving or mineralizing.

International regulations

The OSPAR and London Convention regulations require a post-cessation, site-abandonment plan. They state that monitoring should be continued until "confirmation that probability of any future adverse environmental effects has been reduced to an insignificant level". They leave the final decision up to the relevant authority.

The IEA model framework requires that there is no significant risk of future leakage or any other irregularity. All the required data should be summarized within a report on CO_2 behaviour in the reservoir, the modelling results and the anticipated state of the storage system. However, no minimum time period is specified.

European regulations

Article 18 of EU CCS Directive 2009/13/EC requires the operator to show that CO_2 is completely contained and that no leakage is occurring. Further the modelled behaviour should match the predictions and the storage system should be evolving towards long-term stability.

USA regulations

EPA UIC requires that the operator is obligated to monitor the site to show the location of the plume, the pressure front and to demonstrate that drinking water is not endangered. It is also required to demonstrate that the pressure front and the CO_2 plume have stabilized for at least 50 years after cessation of injection that no additional monitoring is required. This is different to the EU Directive on CO_2 storage where a trend to stable conditions is required. Also the EPA UIC only mentions drinking water and no other environmental impact caused by the site.

The WRI guidance regulations require data on:

- Location, magnitude and extent of plume and the region of elevated pressure;
- CO_2 movement and pressure matches predictions;
- No evidence of significant leakage or failure of confining zone;
- No potential leakage pathway;
- Proven well integrity,

6.3 Transfer of liability

Regulations typically consider the liability transfer of the site after safety of the wells and the CO_2 plume is demonstrated. There is still a discussion about the transfer of liability, as it is suspected that operators may decide differently knowing they will not be responsible in the future. But it is also possible that without such a provision operators may not be interested in any investment concerning CO_2 storage.

In general liability can be separated into four levels:

- *Operational liability* deals with the remediation and monitoring;
- *Environmental liability* is the part about negative effects of CO_2 release on reduction agreements and global climate;
- *In-situ liability* is about the effects on natural site-environment, drinking water, humans and endangerment of hydrocarbon reservoirs in the vicinity;
- *Trans-border liability* concerns the effects on neighbouring countries.

If the safety of the site is provided thoroughly no issues of liability should arise. Nevertheless liability is a vital part of all regulations as to maintain mutual understanding of all involved parties.

The EU CCS Directive requires further monitoring after the transfer of site-responsibility, but other regulations do not. Generally the demonstration of safety is required in every regulation before any transfer of liability is possible, so the extra monitoring required by the EU CCS Directive can be seen as some backup measure.

Some regulations do not specify the financial contributions of the operator, for the understandable reason as that the true costs are not yet clear. But this course may also deter possible operators as they have no estimations on what costs to expect.

After the transfer of liability monitoring of the site is recommendable. The IEA model regulatory framework contains a clause that “the operator should provide suggestions for monitoring after the transfer”. It also mentions a financial mechanism for operators to contribute to a collective fund for expected costs after the transfer.

European regulations

The EU CCS Directive 2009/31/EC says that a certificate for closure will be released after the cessation of injection and the demonstration that all relevant conditions of the permit have been fulfilled by the operator. Also an updated post-injection plan is required, which should be approved by the authorities. If 20 years after site-abandonment the well plugging has proven safe and financial obligations have been met, the transfer of responsibility to the authorities is possible. The kind of responsibility is not specified. So far the operator is obligated to cover any costs related to ensuring the safe containment and they should cover at least the costs of further monitoring for 30 years. After the change of responsibilities the authority will continue monitoring but on a reduced level to ensure no leakage is occurring and to detect any significant irregularities.

The Norwegian petroleum activities act states that authority will make a decision on long-term liability when "Sleipner" is decommissioning.

USA

In the EPA UIC regulations no transfer of liability is mentioned. After the demonstration of the safety of the CO_2 plume and the well plugs a site closure certificate may be granted. As there are strict rules on the demonstration of the plume safety, no additional or further monitoring is required.

IOGCC guidance regulations state that ten years after plugging the wells the responsibility of the site shall be transferred to a designated federal agency and the operator shall be released from his liability. The federal agency will perform monitoring by using a shared fund paid into by the operators. There are no requirements on the safety of the CO_2 plume, but reporting of monitoring, well plugging and removal of installations is obligatory.

The WRI guidance regulations require that when the CO_2 plume and well plugging are proven safe the operator shall no longer be responsible for the site and the future costs. Risk assessment should be updated and periodic monitoring maintained, but it is not yet decided who will be responsible and how to finance further monitoring.

Australia

OPA regulations require an application for closure, including the demonstration of safety and a further plan on long-term monitoring after closure was granted. If closure is granted then the liability is transferred to commonwealth.

The "Victoria Greenhouse Gas Geological Sequestration Act 2008" requires demonstration of safety and a risk management plan but does not specify general liability. The "New South Wales Greenhouse Gas Storage Bill" describes how to apply for site-closure and states that after closure certificate is granted the operator is released from liability.

6.4 Conclusions

There are sometimes large variations in the requirements concerning modelling, risk assessment, monitoring and safety demonstration between the different regulations. However the standard is that these requirements are met already during application in an after-injection plan, approved by the competent authorities. There are few prescriptions of the requirements during the closure and post-closure stadiums, as there are no projects within this time-frame yet, but better definitions of necessary tasks would lead to better understanding on the operator's part.

In general not requiring any particular monitoring techniques allows for an application of updated technologies and methodologies. OSPAR FRAM, which provides a really good basis for modelling and risk assessment, specifies instead the outcomes of the risk assessment which will lead to desired results in a flexible environment.

CO_2 safety can be split up in three main parts: demonstration of no leakage, demonstration of conformity with prediction models, demonstration of long-term stability. An additional requirement may also be the demonstration of no possible environmental endangerment. Demonstrating no leakage is dependent on the used monitoring system, which should be suited for the site-specific requirements. So far no regulation permits leakage, but this condition is severely discussed as it may be necessary to allow minor leakage in some cases. This discussion is also linked to the definition of leakage, which also varies within the regulations. Furthermore there is an obvious limitation of demonstrating the safety by comparing model predictions and monitoring. Diffuse leakage may be found but not detected with the used monitoring time interval. There are also a number of different geological models or scenarios matching the observed data but with different risk factor, therefore any conformity with the observed data may not demonstrate safety.

And there are still certain points which will need to be addressed during the development of the regulations for closure and post-closure of CO_2 storage. Is any leakage acceptable? What about the environmental impact and the leakage rates? If diffuse leakage occurs with a small amount of CO_2, remediation may be unfeasible, but what if the environmental effects were minor? Is the requirement of no leakage too restrictive?

7 CONCLUSIONS AND RECOMMENDATIONS

A number of countries worldwide have implemented regulations regarding CO_2 storage into national laws with the intention to help efforts to reduce greenhouse gas emissions. This report provides an extensive overview of the regulatory frameworks related to operational and safety risks of geological CO_2 storage in countries where the process of implementation has developed furthest (EU, UK, Norway, USA, Canada, Australia), and of applicable international conventions. For the EU region, the main focus is placed on the CCS Directive, which has already been transposed into national legislation in 20 of the 28 the Member States. The materials presented discuss regulations in relation to risks during different stages of the CO_2 storage site lifetime and considering specific activities or events that may occur, i.e. site operation, potential leakage events, monitoring, remediation, closure and post-closure.

Risks concerning CO_2 storage operation can be classified as health, safety and technical risks, which may occur in the local environment and be affected by injection activities, the CO_2 stream composition, pressure and temperature. The operational phase of a storage site, when large amounts of CO_2 are handled, is generally considered as a higher risk phase, as the introduction of CO_2 into the reservoir poses a large change to the reservoir conditions. Regulations are, therefore, most advanced for this phase.

Storage site integrity and by extension leakage prevention during CO_2 storage operation is important for both the success of a CCS project, in order to ensure that there are no significant adverse effects on the environment and human health. Different potential leakage pathways (natural and manmade) each pose different possible risks. Monitoring requirements that exist in all legislations are stream volume, pressure and temperature, in order to determine the amount of CO_2 injected. Under the CCS Directive, when leakage is identified, the CO_2 released into the air or into the water column needs to be quantified according to the ETS Directive Monitoring and Reporting Guidelines.

In case of leakage, indirect effects of CO_2, such as acidification, are also important. Additionally, the mobilisation of contaminants such as heavy metals, and the presence of trace elements in the CO_2 stream pose an appreciable risk. Therefore, to prevent infrastructure corrosion and additional risk, the CO_2 stream should consist overwhelmingly of CO_2 and should contain only traces of other substances. In Europe, it is specifically forbidden to add any substances, with the exception of those used for monitoring. Natural emissions of CO_2 into the environment, at analogue sites, can and are being studied extensively in order to assist in setting CO_2 storage related emission limit. However, currently there are no general safety regulations for CO_2 concentrations in the environment, except for occupational guidelines.

Monitoring is necessary to provide a guarantee that stored CO_2 remains contained, and to identify leakage. In every regulation that was reviewed, regular monitoring reporting to some kind of competent authority is requested, as is notifying this authority in case of a significant irregularity. The definition of a competent authority itself differs from one country to another. A large difference also exists between on- and offshore storage. For onshore storage, the focus lies mainly on protecting valuable groundwater resources, while this is not important for offshore storage.

An overview of (publicly available) monitoring plans of a limited number of active and non-active integrated CCS projects is also provided in this report. Measurement, monitoring and verification are the most important steps in risk management for CO_2 storage. A long list of monitoring techniques are available and under development for specific parts in specific situations. In order to deal with the specific nature of geology, it is preferred that requirements for monitoring in regulations are risk- and objectives-based, site specific and non-prescriptive in the selection of monitoring techniques. Though differences can clearly be identified, all examples follow this site-specific and risk-based approach for defining the monitoring plan. In all cases mainly (existing) wells were identified as potential leakage hazards.

Possibilities for remediation in case of leakage form an integral part of risk management regulations for CO_2 storage. Unexpected reservoir behaviour and potential leakage can have a natural (geological) or man-made (accidents, engineering) cause. A number of remediation measures are available from oil and gas production experience. These measures are generally applicable to man-made causes, mainly to problems with well leakage. Remediation measures for the geological system are rather limited and only partially effective. These include reservoir pressure management and injection of substances for blocking CO_2 migration.

The different risk and safety aspects are closely related and therefore the same regulations are in many cases applicable to multiple aspects. On the other hand, different regulations are often applicable to a certain aspect or region, which leads to some issues in unclear and occasionally contradicting legislation.

Several documents are available that regulate the different aspects of storage risk. At international level, the London Convention and London Protocol were installed to protect the marine environment from disposal of waste. Geological storage of CO_2 is, unlike storage of CO_2 in the water column, is not considered as waste disposal. Under the United Nations Convention of the Law of the Sea (UNCLOS) it is, however, not clear if offshore geological storage of CO_2 is regarded as waste disposal. A consensus between the UNCLOS Convention and the London Convention and Protocol is recommended to clarify the legal status of offshore storage.

For the EU, the CCS Directive and the ETS Directive apply directly to the geological storage of CO_2. Other related regulations are those for waste, waste transport and (ground)water. Offshore, the OSPAR Convention for the protection of North-East Atlantic marine environment also applies to storage risks. Similar to the UNCLOS Convention, the Marine Strategy Framework Directive (MSD) in the EU does not mention CCS explicitly, but such activities might fall under the definition of pollution.

In the US, regulatory competence resides both on federal and state level authorities. At federal level, the US EPA Underground Injection Control fits under the Safe Drinking Water Act. A comparison of regulations revealed some monitoring and liability issues that still need to be clarified. Moreover, there is no mention of a long-term stewardship or a public register of storage sites.

In Canada, jurisdiction is also split between federal and provincial level, with regulations currently present in four out of ten provinces. In Alberta for example, the Alberta Carbon Capture and Storage Statutes Amendment Act and Carbon Sequestration Tenure Regulation provide an enabling framework and storage project regulations respectively. Additionally, a CCS Regulatory Framework Assessment was initiated to identify regulatory gaps and make recommendations.

A different approach was taken in Australia, where amendments are made to the existing petroleum legislation under the Commonwealth Offshore Petroleum and Greenhouse Gas Storage Act. Again, state-specific regulations exist as well. In general, Australian legislation is more prescriptive towards measurement, monitoring and verification requirements in comparison with other countries.

Independently form legislation, the IPCC has issued guidelines for the operation of a CO_2 storage site. The IEA also have issued guidelines for implementing CCS regulation into national laws, that is the IEA Model Regulatory Framework.

While the EU regulation is entirely focused on emission reduction objectives, regulations in the US seem more focused on the utilisation of CO_2 (CCUS) including enhanced oil recovery (EOR). Combined CCS and EOR are allowed under the EU CCS Directive, but it are strictly regulated.

Two general pathways of implementing regulations for CO_2 storage risk management are implemented in the various international jurisdictions. Either a completely new set of regulations is adapted, or existing laws on environment and subsoil use are adjusted. In general, all regulations have the following corresponding requirements regarding risk management:

- The CO_2 stream must be pure, and any other incidental substances cannot be added with the aim of waste disposal.
- Monitoring of the storage site is required before (baseline), during, and after injection.
- Any leakage should be prevented. The exact definition of leakage however differs significantly.
- In case of irregularities, competent authorities have to be informed and measures must be taken according to a risk management plan.

Main differences exist in the definition of the storage volume, periods, liabilities, liability transfer, requirement of monitoring techniques, and technical requirements for site closure (e.g. thickness of cement plugs).

Recommendations

Based on this regulatory overview, several issues regarding CO_2 storage risk legislation could be identified. A number of these are already addressed by the instances involved. Recommendations are given here with the objective to facilitate permitting and administration, but also to create more transparency on liabilities and to facilitate the commercial introduction of CCS.

- Because regulations on storage are elaborate and newly introduced, overlaps with other national and international legislations exist that interfere and sometimes contradict them. Overlaps generally occur between specific and non-specific CCS legislation such as those for water or waste management. These overlaps need to be properly addressed, and care must be taken to ensure transparent and stable regulations for the (storage) operators. Most overlapping legislations are currently undergoing revision.
- Leakage is not uniformly defined in different regulations. This should pose no direct problems, but again different and contradicting regulations might apply to the same project. Moreover, diffuse leakage may be present but not detected with the monitoring equipment used in the monitoring time interval. Such situations are currently insufficiently addressed.
- The utilisation of CO_2 (CCUS, EOR etc.) could provide the business case for jumpstarting wide-scale deployment of CCS technology and appropriate and transparent regulations should be available. Complementary regulations between oil and gas production and CCS activity is therefore needed. In general, developing a CCS legislation can benefit from experience in the oil and gas industry and legislation.
- For all legislations the long-term liability provisions need further revision and consolidation. There are few prescriptions of the requirements during the closure and post-closure stages, as there are no projects within this timeframe yet. Better definitions of necessary tasks would lead to better understanding of expectations on the operator’s part. Especially under the USEPA regulations there is no description of transfer of liability for long-term stewardship after site closure, while this aspect receives significant attention in the EU CCS directive.
- Specifically for the EU, the ETS Directive contains minimum competency requirements for the verifier of the monitoring and risk assessment reports. In the CCS Directive however, there is no mention of such requirements. It may be worth considering the introduction of standards for verification bodies regarding their knowledge, experiences, independency etc. This may result in the introduction of an accreditation procedure for verifiers under the CCS Directive at different levels (national, international).
- Uncertainties are a specific issue in geology. It should be clear how these uncertainties should be handled and the the confidence levels are required in modelling as well as the accuracy levels required in the monitoring used to verify modelling results. Uncertainty management and confidence/accuracy requirements on all storage aspects should be included and set realistically, for a given storage site setting.

- Currently, there is no obligation to keep a public register of storage sites under the US EPA regulations, nor in the IEA MFR guidelines. Although the level of disclosure that is necessary is still under discussion, such a register could increase public confidence.

This review has revealed that for countries that have a dedicated CCS regulation, although some issues still exist, most risks are covered. For countries looking to implement regulations, guidelines exist and installed legislation can serve as an example. Because CCS is a relatively new technology, experience will also guide new regulations. As investment and environmental risks are large, regulators need to be sure that risks are properly managed and operators need to be confident that liabilities are covered.

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