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ScienceDirect

Energy Procedia 63 (2014) 3242 – 3252

Energy Procedia

GHGT-12

A guide for assessing the potential impacts on ecosystems of leakage from CO_2 storage sites

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Abstract

Evidence to date indicates that leakage is of low probability if site selection, characterisation and storage project design are undertaken correctly. In Europe, the Storage Directive (EC, 2009) provides a legislative framework, implemented by Member States, which requires appropriate project design to ensure the storage of CO_2 is permanent and safe. However, it is incumbent on storage site operators to demonstrate an understanding of the potential impacts on surface ecosystems should a leak occur.
The RISCS (Research into Impacts and Safety in CO_2 Storage) project has produced a Guide to potential impacts of leakage from CO_2 storage (the 'Guide'). RISCS assessed the potential effects of CO_2 leakage from geological storage on both onshore and offshore near-surface ecosystems and on potable ground water. This assessment was achieved through laboratory and field experiments, through observations at sites of natural CO_2 seepage and through numerical simulations. The Guide summarises some of the key findings of the project.
The Guide provides information on the best approaches to evaluate potential impacts of hypothetical leakage from CO_2 storage sites and to provide guidance on appraising these impacts. This information will be relevant to regulators and operators in particular, but also to other stakeholders who are concerned with CO_2 storage, such as national and local governments, and members of the public.

Peer-review under responsibility of the Organizing Committee of GHGT-12

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doi:10.1016/j.egypro.2014.11.351

Keywords: Leakage, ecosystem impacts, CO_2 storage, risk assessment

1. Introduction

The Guide considers the potential impacts of leakage. This information could be used when assessing the potential risks during detailed project design, enabling specific aspects of the site characterisation to be planned. Once site selection and characterisation has been undertaken, the information provided by the Guide could be further used to develop environmental monitoring plans. Corrective measures plans (mitigation and remediation) and site closure plans might also benefit from consideration of the Guide. Regulators and other stakeholders might also use the Guide to assess the appropriateness of those plans. The Guide does not make specific recommendations for a formal Environmental Impact Assessment, although the information should be relevant for this type of assessment.

The assessment of environmental impacts will be a key feature of the design and permitting process for CO_2 storage projects, and will focus mainly on the potential impacts arising during the construction of infrastructure and during the routine operation of the storage site. Potential impacts arising from the leakage of CO_2 following injection may be considered as part of the assessments, as a regulatory requirement. The Guide specifically addresses potential impacts following leakage of CO_2 from geological storage; although similar impacts could also arise from leakage from pipelines, these have not, in general, been considered explicitly.

The RISCS project has specifically undertaken research into the potential impacts of leakage in a European regulatory context, in both terrestrial and marine environments of most relevance to Europe. However, some of the results obtained should be of wider relevance for similar environments elsewhere and under other regulations. The Guide and supporting research focussed on the impacts of leakage rather than the processes leading to leakage within the reservoir or caprock.

The RISCS project conducted a broad range of research to understand the possible impacts that might occur in the event of CO_2 leakage from geological storage systems. Issues relating to CO_2 injectivity, storage capacity and containment integrity were outside the project's scope. Similarly, the potential impacts of water or other formation fluids being displaced from the storage complex by injected CO_2, even though the CO_2 does not itself leak from the storage complex, were also not considered, although it is noted that these impacts could potentially be significant. A significant amount of information is already known about the potential impacts of brine displacement from studies of aquifer salination.

2. Leakage Scenarios

Hypothetical leakage scenarios enable developers of a CO_2 storage project to:

1. Illustrate to stakeholders, including regulators, that the consequences of unexpected CO_2 leakage are understood; and thereby
2. Enable stakeholders to understand where impacts are insignificant and in what circumstances mitigation would be required.
3. Develop mitigation plans
4. Develop efficient monitoring strategies

These scenarios are needed because regulations require the possible impacts of leakage to be discussed while at the same time demonstrating that leakage has not been detected; the scenarios make no a priori assumptions about leakage probability.

Each leakage scenario defined here consisted of general descriptions of a reference environment, including its climatic conditions and/or water depth and salinity (in the case of marine scenarios) and kinds of ecosystems that occur. The 'receptors', which are those components of a reference environment that could be impacted by any CO_2 that were to leak, include biota and ground water aquifers that might be exploited for drinking water. The CO_2

leakage characteristics are defined in terms of the leakage pattern and consequential emission pattern (and quantity) at the surface of the solid earth, whether the CO_2 is a free phase or dissolved in water and the kind of dispersion of CO_2 after leaving the surface of the solid earth (in the case of aquatic environments).

The following scenarios were defined for leakage pathways in terrestrial environments:

- Normal Evolution Scenario (no leakage). This is expected to be the most likely scenario for the majority of storage sites where site characterisation and design have reduced the potential for leakage.
- Direct release to the atmosphere, via a well (high flux for a relatively short time period – e.g. days);
- Localised release to soils as a result of wells/faults/fractures, leading to high concentrations of CO_2 in the near surface;
- Localised release to soils as a result of wells/faults/fractures, leading to long-term low concentrations of CO_2 in the near surface;
- Localised release to freshwater lakes via fractures/faults;
- Diffuse releases to surface and near-surface systems;
- Localised release to aquifers that may be exploited as drinking or irrigation water resources; and
- Release to an urban environment.

The following scenarios were defined for leakage pathways in marine environments:

- Normal Evolution Scenario (no leakage);
- Localised direct release of free CO_2 via the sediment or directly to the water column above the sea bed via a point source;
- Diffuse direct release of free CO_2 via the sediment or directly to the water column over a wide area;
- Localised release of CO_2-charged water through the sediment or directly to the water column via a point source; and
- Diffuse release of CO_2-charged water through the sediment and subsequently to the water column over a wide area.

3. Reference Environments

The Guide aims to build confidence among stakeholders such that, if the suitability of a particular European CO_2 storage site was to be assessed in the future, the potential impacts of any CO_2 leakage, if it occurs, can be evaluated and understood adequately. A related aim is to provide guidance on how these potential impacts can be evaluated. Given the expected large range in environmental characteristics between individual sites both on- and off-shore, it is impractical to investigate all possible kinds of sites in a generic study of the kind undertaken in RISCS. Consequently, the approach taken was to research potential impacts within a few different kinds of environments (henceforth termed ‘generic environments’) that collectively contain all the important features and processes that might cause leaking CO_2, if present, to impact on sensitive domains above an actual storage site. It is likely that an actual CO_2 storage site will not be exactly like any of the generic environments. However, it is expected that the important features and processes that influence potential impacts within the actual storage site will occur within one or more of the generic environments. Consequently, by providing evidence to stakeholders that potential impacts within all the generic environments can be assessed adequately, the Guide will contribute to confidence among the stakeholders that potential impacts at the actual storage site can be assessed sufficiently. Similarly, based on experience gained by investigating and assessing potential impacts for the generic environments, techniques can be demonstrated that are appropriate for investigating and assessing potential impacts in any actual CO_2 storage site.

A small number of reference environments, including both marine and terrestrial examples have been defined (Table 1). The environments together explore a representative range of receptor classes within the two main broad categories, to give an indication of the range of features, events and processes that need to be considered when investigating potential impacts of CO_2 leakage.

Table 1 Reference environments defined in the Guide.

	Reference environments	Notes
Terrestrial	Maritime temperate	Representative of a northern central European, cool climate (e.g. UK and the Netherlands). The region is highly developed and has some of the world's highest population densities. Potential environmental risks from CO2 leakage apply mainly to the root systems of agricultural crops, to soil microfauna or larger soil dwelling animals and to exploitable ground water supplies.
	Continental	Climate associated with northern (but not Arctic) European continental land mass countries. The distribution of this environment corresponds broadly to the distribution of 'boreal forest' and extends as far north as the tree line. The environment is characterised by some of the lowest population densities in Europe. It also covers most of Sweden, Finland, and much of Norway.
	Mediterranean	Representative of warmer, more arid, southern European climates. The tree, bush and dwarf shrub dominated habitat types (forest, scrub and heath lands) occupy more than half of the region's landscape. Dense forests occur mostly in plantations or in natural forests under humid conditions by wetlands or in valleys.
	Generic urban	Specifically designed to explore potential impacts on humans should a storage system be located close to a large urban centre. At high concentrations, the principle risk is asphyxiation, particularly where CO_2 concentrations might increase in confined environments such as cellars. Detailed studies of the physiognomic effects of CO_2 are beyond the scope of this Guide and have not been considered in the RISCS project.
Marine	Cool, temperate, deep	Continental shelf remote from shoreline influences where the water depth is greater than 60 m, and typically over one hundred metres. Tides significantly influence mixing and currents but not water depth. The environment is not Arctic (no sea ice), but bottom water is cool (around 5°C). The moderately nutrient rich water is seasonally stratified, surface temperatures varying from around 4°C to around 15°C annually. Such an environment may be in the northern North Sea, or to the west of Norway south of the Arctic Circle.
	Cool, temperate, shallow	Land is relatively close and the water depth is a few tens of metres. A comparatively large tidal range could cause significant changes in water depth and strong mixing. Some seasonal stratification may occur but normally the water column is fully mixed. The temperature varies from around 4°C to around 15°C annually. Nutrient rich (eutrophic) water may be impacted by riverine water. An example could be in the southern North Sea.
	Warm shallow	Land is relatively close and water is a few tens of metres deep. The tidal range is small. Variable seasonal runoff from adjacent land masses may be significant. The temperature is a minimum of 5°C at the seabed and varies annually from 6°C to 25°C, with a mean of 10-12°C, at the sea surface. Such a site could be in the Adriatic Sea.
	Low salinity (saline, but	Land is relatively close and water is a few tens of metres deep. The tidal range is small. Water salinity is much lower than that of open ocean water (which is present in the other

	lower than mean ocean salinity)	marine environments), but varies depending upon the proximity of the coast and open ocean. Biodiversity is much less than in the open-ocean. Such an environment would be in the Baltic Sea.

4. Terrestrial Impacts

4.1. Baseline studies

Baseline studies need to cover the range of ecosystem and aquifer types within the project area and account for natural variability on different timescales (e.g. daily, seasonal, year on year). Results from the RISCS project suggest that the following should be included in baseline studies:

1. Soil gas concentrations and fluxes**.** The impacts of potential CO_2 leakages on ecosystems can only be evaluated if the baseline CO_2 soil gas concentrations and fluxes are available for any site. CO_2 soil gas concentrations above 10% may impact on terrestrial ecosystems. Thus CO_2 soil gas concentrations above this concentration that were detected during the site characterisation phase would require further investigation to establish the cause.

2. Plant surveys**.** Differences in sensitivity in different species have been observed at all the RISCS project sites with grasses generally being more resilient than other plant types. Plant stress is detected where CO_2 concentrations are above 10% at 30 cm depth in the soil, although this concentration is within measured levels in natural soils in some areas. Plant stress is manifested by discolouration of leaves (loss of chlorophyll). If exposure is stopped plants are likely to recover, but if exposure continues, plants are likely to die in less than four weeks. Additionally, poorly draining soils with high moisture content reduce CO_2 dispersal into the atmosphere. Thus baseline surveys should establish the land and agricultural use of a site, including the flora and soil type prior to any CO_2 injection. This would include any possible changes in crops in agricultural areas.

3. Soil microbiology surveys**.** Increased CO_2 concentrations have a complex impact on microbial populations which is difficult to interpret. Nevertheless, at sites where there has been prolonged exposure to high CO_2 concentrations, the microbial community has adapted to this environment with acidiphilic, anaerobic populations predominating. The RISCS project has not determined the significance of these changes with regard to soil fertility. Baseline studies could include an analysis of the microbial community present in the soil at a variety of depths so that any changes could be monitored in the event of leakage. Such analysis would be performed in areas of particular sensitivity, such as protected sites and would be undertaken once to establish baseline conditions, due to the expense of the surveys and the variable nature of microbial populations.

4. Ground waters**.** A good understanding of an aquifer will require knowledge of the geology (lithology of the aquifer) and hydrogeology (flow and hydrodynamics) but also the 'baseline' conditions of mineralogy and water chemistry prior to CO_2 injection. This will help identify the potential impacts on the potable ground water resource. Baseline monitoring of aquifers will be required in all reference environments where ground waters are used, or could be used in the future, for fresh water supply. Some of this monitoring may be undertaken already if the aquifer is used to supply drinking water.

   a. Baseline monitoring of a drinking water aquifer prior to deep injection is strongly recommended, with a wide range of parameters being measured in different areas and over different seasons to ensure a complete characterisation of the chemistry and spatial and temporal variability of the aquifer. This could include all carbonate system parameters, major and trace elements, dissolved gases and redox level. For example, work at the Florina site has shown seasonal variability of ground water chemistry as a result of recharge rates in rainy versus dry periods of the year.

   b. Mineralogical analyses of the aquifer are also desirable to aid in geochemical modelling and computer simulations of potential impacts, especially analyses of carbonate mineralogy for buffering capacity and of oxides for redox buffering and potential trace metal contents. The importance of site mineralogy was clearly shown at Latera and San Vittorino, where volcanic rock mineralogy at the former versus a carbonate mineralogy at the latter greatly influenced the level of impact and the specific changes in the water chemistry caused by the naturally-elevated CO_2. At San Vittorino, the greater buffering capacity of the carbonate lithologies reduced the potential changes in ground water chemistry caused by the CO_2.

c. Specialised geochemical analyses can greatly aid interpretation of water rock interactions, as demonstrated at Montmiral. In shallow ground waters at Montmiral, water-rock interactions were assessed to determine that the observed reactions were caused by water in contact with a biogenic CO_2 soil reservoir. Lack of interaction with gaseous CO_2 of a deep origin was also confirmed by the absence of a $\delta^{18}O$ shift towards more negative values as observed for example in the neighbouring Massif Centrale. Accurate interpretation of the data from these baseline ecosystem studies will need to take into account other information including weather (such as temperature, precipitation and wind) and any other factors which might also impact on the health of the ecosystem.

Repeat baseline studies may need to be undertaken over a period of several years depending on regulatory demands and the seasonal variability at the site itself. Monitoring may be needed, for example, for between two and five years to sufficiently capture the expected range in natural variability. Indeed, it may be prudent to undertake baseline surveys over long periods to determine changes resulting from other factors such as land-use changes and climatic variations. For some parameters, like soil gas concentrations and fluxes, continuous monitoring stations can be deployed to better define long-term (e.g. seasonal) variability at key locations. These can be used to extend baselines into the injection phase of a storage project, provided that no leakage occurs, and could help to identify underlying longer term trends.

Seasonal effects on plants and near-surface ecosystems, such as changes due to temperature, precipitation, and/or day length will impact plant growth and activity. Thus there is limited benefit to monitoring of terrestrial ecosystems in the winter when growth is very limited because any impacts are unlikely to be detected, although near surface gas monitoring is often best in late autumn or winter when biological CO_2 production is at its lowest.

Plant response to increased CO_2 soil gas concentrations is very rapid. The threshold for observing responses appears to be at about 10% soil gas concentration at shallow depth (30 cm). Between 15-20% CO_2 at this depth, results indicate that broad-leafed plants become stressed within 7-14 days of exposure during the growing season and then die after a few weeks of continued exposure. However, plants with root systems that are well developed before exposure might be more resilient to subsequent increased CO_2 concentrations. For example, autumn-sown crops which were then exposed to CO_2 leakage in the following spring were less susceptible.

Although CO_2 leakages have the potential to cause large decreases in yields from crops with short growing periods, such decreases are likely to have little economic impact because leakages are most likely to take place over small areas. Indeed, impacts may not be detected until harvest. This must be viewed in the context of other environmental stressors (e.g. weather extremes, disease and pests) which are likely to have greater overall impacts on crop yield. For well-established pasture, the impacts of CO_2 leakage on yields for animal feed might also be minimal, though need to be evaluated carefully to establish whether there is a significant long-term (over several years) economic loss.

4.2. Recommendations for terrestrial sites made in the Guide

- Ecosystem baseline surveys should be carried out at proposed storage sites to ascertain any changes resulting from leakage. These will also assist in Environmental Impact Assessments. It would also be beneficial if reference sites were similarly assessed and monitored so that any ecosystem changes attributed to CO_2 leakage can then be compared to changes at the control site.
- The significance of impacts from a credible leakage scenario on near surface ecosystems is expected to be very low, relative to other types of environmental damage such as climate change and extreme weather events.

However, the significance of any leakage will depend on when it occurs (i.e. leakage during the growing season is likely to be more damaging than in winter) and its duration before detection and potential remediation. Additionally, marginal terrestrial environments, such as those with very short growing seasons, may be more sensitive to CO_2 leakage although this was not studied in the RISCS project. Consequently, it is important to take into account the context of leakage when assessing impacts on terrestrial ecosystems for a particular storage project.

- Storage projects should, as a minimum, undertake regular CO_2 soil gas evaluations at a variety of scales (metre to kilometre scale) and depths. It is not recommended to undertake ecosystem monitoring in the winter because ecosystems are much less active at this time. Initially, two to three surveys might be undertaken per year to define baselines although this will depend on land use.
- The RISCS project has shown that short term exposure to elevated CO_2 has no long term effects for many crops. Affected crops should either be allowed to grow until harvesting or should be replanted. The decision on the approach will depend on economic considerations and the timing of leakage. However, recovery in pasture and after long-term exposure to elevated CO_2 concentrations is unclear and it is recommended that further research is undertaken to clarify these uncertainties.
- Further research should be undertaken to understand the effects of ecosystem changes on soil fertility arising from elevated CO_2 soil gas concentrations. Research into the potential use of bio-indicators as quick monitoring techniques should also be carried out.

5. Marine Impacts

5.1. Baselines

The natural variation in pH can be significant over relatively small spatial and temporal scales, and in some cases diurnal signals can approach the magnitude of seasonal variability. Over an annual cycle the acidity in seawater will vary by 0.2-1.0 pH units (typically 0.3-0.4 pH units in shelf seas. Frontal systems and biological features such as blooms also give rise to significant spatial discontinuities. This variability is greatest in well-lit surface waters, where most of the primary production (photosynthesis) occurs. Primary production associated with benthic systems occurs only in shallow regions (<20 m) of relatively turbid waters like the North Sea but may occur at depths of up to 100 m in relatively clear waters (as found in some parts of the Mediterranean). At the benthic surface, where leakage signals are most likely to be apparent, the main biological process is respiration which can create locally significant increases in CO_2.

If leaked CO_2 appears at the sea floor in gaseous form it will be buoyant and form a rising bubble plume. Concurrently, as CO_2 is highly soluble in seawater, it will dissolve rapidly. The RISCS project has not explicitly researched bubble plume dynamics, but relying on published information we can be confident that bubble plumes will generally dissolve within 10 m of the seafloor. Seawater with a high concentration of dissolved CO_2 has a higher density and will tend to sink relative to 'normal' seawater. This effect is likely to create a plume of higher CO_2 concentration near the sea bed over several tens to hundreds of metres from the source. As a result, most environmental impact is predicted to occur at the sea floor, to benthic communities and especially sessile, immobile biota.

Whilst the epicentre of a leak is likely to induce a pH significantly lower than found naturally, this might be confined to a small volume and be difficult to detect. The surrounding area affected by the leak will likely show deviations similar to that expected due to natural variability.

5.2. Impacts

The scale of biological effects that can be expected as a consequence of leaking CO_2 depends on the local biological situation, such as the presence of sensitive species/life stages and food availability. In addition, physical circumstances can play a role. In the warm shallow marine reference environment (such as the Mediterranean), there is some indication that temperatures make a difference to the impact from elevated CO_2 exposure on some marine organisms such as crabs. However this was not observed in the cool temperate shallow marine environment (such as the North Sea). However, it should be recognised that temperature changes can also have an indirect effect on habitat and species, by altering the balance between components of the food chain.

Populations that are already living under less favourable conditions (such as food and nutrient shortage, lower oxygen levels, sub-optimal salinity or temperature) are likely to be more vulnerable to the impact of elevated CO_2 concentrations than populations experiencing optimal environmental conditions. This will also be the case for populations that are exposed to anthropogenic pollutants, especially since some dissolved heavy metals become more toxic at lower pH values due to their increased bioavailability.

Apart from the sensitivity of the ecosystem during the leak, the vulnerability of an environment is also determined by the capacity to recover after the leak has been stopped. Simulations suggest that once the CO_2 flux is ended recovery to normal CO_2 levels can be expected, typically within days in the pelagic system, although less is known about the benthic system. This implies that an area that has been negatively impacted by a CO_2 leak is available for re-colonisation soon after the leak has been stopped. Therefore if the area that is potentially affected by a CO_2 leak is relatively small, in most situations unaffected populations of the affected species will be present in the neighbourhood. The majority of the sessile marine species have a high reproductive potential, often with planktonic larval stages that are widely distributed by water currents. It may therefore be expected that recovery of an affected community can occur rather quickly, at least with respect to species diversity. Evidently, it will take longer for longer living species to recover to the original age structure of the population. However, impacts on habitat-creating organisms, like deep sea coral reefs, might affect the whole community that depends on the reef structure as a habitat. Hence, recovery strongly depends on the degree of connection with other populations. The more isolated populations are, the longer it will take them to recover after the CO_2 leakage has been stopped.

5.3. CO_2 dispersion in seawaer

Dispersion of CO_2 plumes in seawater is a complex process. Initially highly buoyant gaseous CO_2 dissolves rapidly, forming potentially dense plumes of water containing higher concentrations of CO_2 that will tend to sink in the water column. Whilst local currents will determine the mean direction of a leakage plume, especially in cool temperate shallow and deep marine reference environments like the North Sea, tidal mixing is the main method of plume dispersion. Generally, tidal movement forces water masses in an elliptical pattern, accelerating dispersion. As shown below the resulting plume revolves around the leakage centre, with implications for both impacts and monitoring.

Model based studies indicate that dispersion can be relatively rapid so that only the neighbourhood of a leak event is likely to be strongly impacted (Figure 16), although this area could be metres or kilometres across, depending on the leakage rate. However, tides and currents will combine to make plume behaviour complex such that the CO_2 concentration and pH is prone to oscillate at any given point in space (Figure 17 and Figure 16). Deeper regions of shelf seas and most oceans stratify seasonally, i.e. when summer heating creates a warm less dense surface layer which does not mix with deeper waters. In such a case, any leaked CO_2 would be effectively trapped below the thermocline, with increased impacts on the benthic system.

Clearly any leakage event will be unique, and it is important to stress that the dispersion from any leak would depend on the flux rate, time of year, depth, tidal strength as well as local topography, the phase nature of the flux and its distribution on the sea floor. We have taken the approach of analysing a selected number of evidence based scenarios that cover the spectrum of leak possibilities, to define the scale of potential impact and broadly assess the areas and volume affected.

We elected to develop a small number of exemplar scenarios based on the leakage scenarios identified in the RISCS project, set into a typical cool temperate marine reference environment. The scenarios investigated included, amongst others, a continuous release of 4T d^{-1}, a temporary leakage of 9000T representing leakage from surface infrastructure and a continuous leakage of 1500 T d^{-1}. For convenience, we have adapted a regional model of the SW English Channel for our purposes, rather than attempt to mimic a specific site that has been identified for storage. Our domain provides conditions that are typical of the NW European shelf in terms of tidal strength and hydrodynamic properties, so that the results can be considered qualitatively transferrable to other regions on the shelf. Bespoke simulations for specific storage sites will require detailed information on local conditions and the explicit design of an appropriate model domain. Such information is available, but would require some dedicated effort.

Previous work suggests that the environmental conditions will have a strong bearing on the evolution of a leak, therefore each scenario has been tested in a range of tidally driven mixing regimes. Damping input flow velocity at the model boundary has been used to produce a weak, medium and strong flow regime with mean current velocities of 0.10 m/s, 0.14 m/s and 0.17 m/s, respectively. These are typical of offshore North Sea conditions.

Intensive water mixing in the area where the CO_2 is released will result in a wider area that is exposed to seawater with typically lower CO_2 concentrations than areas with less mixing or more stratification. This was illustrated during the seasonal sampling campaigns conducted at the natural CO_2 leaking site at Panarea, Italy. In deeper waters during summer, stratification of warm and cold water layers can occur, trapping the CO_2 enriched water near the bottom resulting in higher CO_2 concentrations than in non-stratified conditions. Other forms of stratification, such as those caused by salinity in fjords, which dominate much of the Norwegian coast, may also result in increased retention of CO_2 in the deeper waters. As the biological impact is rapidly reduced with increasing dilution, locations with intensive water mixing and little chance for stratification can thus be considered less sensitive to the impact of CO_2 leakage.

5.4. Site selection

In site selection, the effect of an unforeseen CO_2 leak must be minimised as much as possible. This can be realised by selecting sites with the following characteristics, in addition to the primary requirement to have a geological store that will permanently retain the injected CO_2:

- Regions of unusually low mixing of the water column might be avoided where possible, both from the point of view of dispersing leakage and aiding recovery by colonisation.
- Regions with unusually heavy reliance on calcification as the basis of the ecosystem (e.g. cold water corals) or other unique and sensitive ecosystems should be avoided.
- The ecosystem should not be overly affected by other natural (e.g. low salinity, oxygen depletion, food shortage, etc.), or anthropogenic (pollutants) stressors.

Once a site or region is identified for storage and the likely subterranean footprint of the reservoir complex known it is recommended that:

- The sites chosen for storage are subject to rigorous baseline surveys, drawing on existing data, models and if necessary new observations. This should include the analysis of the normal co-variance of CO_2, oxygen and temperature to aid monitoring interpretation.
- Bespoke simulations of leakage dispersal are made to identify optimal siting of monitoring equipment.
- An analysis of impact potential, based on the above, is developed. Assessment of impacts arising from potential leakage should also consider the cumulative and combined effects of a CO_2 leak as an addition to the stress induced by other marine activities.

6. Recommendations

Evidence to date indicates that leakage is of low probability if site selection, characterisation and storage project design are undertaken correctly. In Europe, the Storage Directive (EC, 2009) provides a legislative framework, implemented by Member States, which requires appropriate project design to ensure the storage of CO_2 is permanent and safe. The work undertaken in the RISCS project, including comparisons with other published results, allows us to draw the following high-level conclusions:

- Impacts from CO_2 leakage are expected to be small compared to impacts caused by other stressors. These additional stressors include, but are not limited to, changes in land use, extreme weather events, periods of abnormal weather and activities such as bottom trawler fishing; and the impacts that CCS seeks to mitigate such as climate change and ocean acidification.

- It is recommended that storage operators and relevant Competent Authorities demonstrate that an appropriate level of understanding has been developed of the potential impacts that might arise if a leak did occur from the specific site being considered for CO_2 storage.

- Evaluation of risks of leakage and potential impacts should be undertaken at each site, since each will have specific characteristics which will influence the nature and scale of the environmental response. The context of what specific impacts mean for a particular storage site (e.g. selection of crops) is fundamental and should be explained where relevant.
- The research undertaken in RISCS and reviewed research published elsewhere indicates that there are no reasons why a storage project could not be sited within any of the large-scale environmental types that have been studied here.
- Potential impacts will be further reduced by careful site selection and appropriate monitoring and mitigation plans.
- All monitoring programmes should use ecosystem evaluation techniques. Monitoring technologies and assessment methodologies have been developed and tested that allow the impacts of CO_2 in terrestrial and marine environments to be assessed.
- Indicator species that occur within specific onshore sites have been identified that can be monitored in conjunction with other environmental factors to assess the scale of an impact and the efficacy of any remediation.

Furthermore, it is concluded that:

- Carefully selected reference sites, both onshore and offshore, could be a powerful tool for providing ongoing baseline data against which storage sites can be compared. They would allow changes related to factors other than CO_2 leakage to be assessed. Sites managed via joint industry initiatives may be a suitable approach to enable a smaller number of reference sites to be developed for use by several storage projects.
- Evidence indicates that areas that might be affected by leakage will be localised. Individual seeps can be up to a few tens of metres across, and groups of these seeps might occur along fault zones. However, the total area of these seeps would still be a very small proportion of the area that might be used for CO_2 storage. This applies to onshore and offshore sites and includes potential impacts on ground waters. This implies that monitoring techniques able to detect leaks at these small scales over large areas should be deployed if leakage is suspected.
- Monitoring a number of parameters in addition to those directly indicative of CO_2 levels will help to separate natural variations in CO_2 content from leakage, such as measuring nitrogen, oxygen and isotopic contents of soil gas or recording temperature and dissolved oxygen in marine systems.
- Baseline surveys will be required and are a fundamental part of demonstrating site performance. Ecosystem baseline surveys should be carried out at proposed storage sites to ascertain changes resulting from any leakage. These will also assist in Environmental Impact Assessments. It would also be beneficial if reference sites were similarly assessed and monitored so that any ecosystem changes attributed to CO2 leakage can be compared to results from the non-injection site.

Specific recommendations for operators and regulators to consider are:

- Site-specific monitoring will aid confidence building and demonstrate that the duty of care for safe, permanent storage has been met appropriately.
- Baseline surveys should be designed to account for a full range of natural variation, which may occur over more than one year. Changes at the storage site due to other external factors should also be taken into account, for example through the use of reference sites. Communication of these baseline results to the local stakeholders (such as residents and NGO's) is advisable to create dialogue and increase knowledge of the natural system and its variability.
- Investigations for storage sites should include an assessment to determine whether the Conservation Objectives of Natura 2000 sites and any other protected areas are significantly affected by the project

- Leaks may have a cumulative, additional impact on ecosystems already stressed by other factors, such as low salinity marine environments, existing contaminated areas or marginal systems that are already restricted in their development.
- The timing and duration of the exposure will influence the scale of the impact. Timing is important because the stage of development of plants and animals affects their response, whilst the ecosystem in its entirety may be able to cope with enhanced CO_2 for a short duration.
- The scale of the likely impacts examined in the RISCS project means that they are considered manageable both by the ecosystem and by relevant stakeholders (operators and regulators).
- Offshore sites where mixing in the seawater column would allow dilution of CO_2 would be preferred because if a leak were to occur the natural mixing processes in the seawater could enhance dispersion and thereby minimise impacts. Similarly, onshore sites that avoid potential build up of CO_2 in confined areas would also be preferred, as under normal conditions light winds can quickly disperse any leaking CO_2.
- Natural recovery in dynamic marine systems is expected to be relatively rapid i.e. mostly within one ‘growing cycle’ or season, due to the large pool of ecosystem resources and small scale of the impacted area, although this may not apply to all scales of leakage.
- In terrestrial systems, replanting of crops should be possible in affected areas once leakage has ceased, as no long term effects are expected based on experiments on crops. However the longer term recovery of pasture land has not been fully evaluated.

7. Acknowledgements

The Guide has greatly benefitted from the support, advice and review of a number of people within the RISCS project for which the authors are very grateful. In particular, Camilla Skriung of ZERO and Samuela Vercelli, of URS, have both been instrumental in ensuring the report meets with the requirements of the intended readership. Further advice and review was provided by the following, who the authors gratefully acknowledge: David Hilditch of the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), Lee Spangler of Montana State University, Tim Dixon of IEAGHG, Malcolm Wilson of University of Regina, Matt Baggaley and Tim Hill of E.ON New Build and Technology, Ines Koehler of Vattenfall, Alv-Arne Grimstad of Sintef, Thomas Thielemann of RWE, Tore Torp and Aina Janbu of Statoil.

The Guide has also been reviewed by a range of external stakeholders including representatives from relevant industries, environmental non-governmental organisations (NGOs) and some regulatory bodies, who the authors gratefully acknowledge.

The research leading to these results has received funding from the European Union‘s Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 240837 and from industry partners ENEL I&I, Statoil, Vattenfall AB, E.ON and RWE.