An early phase risk and uncertainty assessment method for CO₂ geological storage sites

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Abstract

Early phase risk assessments of prospective CO₂ storage sites are frequently characterized by a lack of knowledge, or high degree of uncertainty, in the relevant geological characteristics. The methodology presented here attempts to address this challenge by using facilitated expert workshops to rank key knowledge gaps and risks in order to form the basis for future site characterization work. Taken in the context of the CO2QUALSTORE guideline, the goal of such characterization work should be to provide the evidence required to pass the next decision gate in the project. The degree of involvement from national or regional authorities in this process is likely to be greater where performance based regulations are in place and the current methodology is designed to facilitate this interaction if required. In one of the two European case studies discussed here, Vattenfall have actively engaged the relevant authorities in Germany in the risk assessment process, thus laying the groundwork for future dialogue around characterization requirements and storage site risk management.

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1. Introduction

Risks and risk based decision-making are common in our everyday living, even though the risk concept differs between different applications. Risk management is the all-embracing process of coordinating an organisation with regard to risk. The wider risk management process is about using the outcome from the risk assessment together with risk treatment, risk acceptance and communication of risks. To implement Carbon Capture and Storage (CCS) in a safe and sustainable way, there is a need to apply risk management best-practices and actively pursue constructive engagement between industry, regulators and the general public. Furthermore, to build confidence in CCS as a trustworthy option to mitigate global warming, it is important that CCS projects are implemented in a clear and transparent way that stakeholders can accept, where opportunities and risks are balanced and well

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This background provided DNV with the motivation for coordinating the CO2QUALSTORE joint industry project that published a guideline for the selection and qualification of CO₂ storage sites in April 2010 [1], [2], [3]. Vattenfall was one of the partners in this project and contributed their experience with risk assessment of prospective storage sites that pre-dated and ran in parallel with the project. DNV was contracted by Vattenfall to perform two such studies between June 2008 and February 2009 and the methods used are presented here. These studies were outside the remit of the CO2QUALSTORE project, but were carried out in a consistent manner.

2. Background

Risk assessment of geological storage for different purposes is not new and experience with suitable methods has been documented [4], [5], [6]. One suitable methodology for assessing the long-term risks with CO₂ storage is the performance assessment approach developed for nuclear waste disposal. This method has been adapted to fit CO₂ storage in, for example, the European research projects CO2STORE [7], CO2SINK [8] and CO2REMOVE [9]. This method includes an analysis of features, events and processes (FEPs), a process driven, top-down development of probable scenarios and a probabilistic system model for evaluation of the scenarios. An example of application is the risk assessment on the Schweinrich structure in Germany in 2005 as part of the CO2STORE project [10].

Both Vattenfall and DNV have long-term engagements in supporting development of methodologies to assess CO₂ storage related risks and both companies cooperated in testing the set of tools presented here, which are consistent with the performance assessment approach described above. These tools are applied in a workshop environment and make use of a range of discipline experts from inside and outside the project organisation. They are well suited to the screening and assessment of storage sites, but need to be complemented with more detailed assessments, data collection and modelling for the later design and operation of CCS sites. The three main tools used are as follows:
- a Structured What-IF Technique (SWIFT) for the comprehensive identification of geological risks;
- a semi-quantitative risk ranking;
- a spread-sheet tool for assessing the quality of, and confidence in, primary and secondary reservoirs and seals.

This methodology has been applied and tested on five specific sites; two offshore sites in Norway and the Vattenfall CCS project developments in Denmark (one site for the Nordjyllandsværket power plant) and Germany (two sites for the Jänschwalde power plant). This paper will present experience gained with the Vattenfall projects, lessons learned and suggestions for further work.

3. Risk and uncertainty assessment in a CO2QUALSTORE context

The CO2QUALSTORE guideline provides a framework that the risk assessment process described in this paper fits into. The guideline does not offer a timeline for CCS project development, but rather a logical sequence of milestones, or stage-gates and their associated criteria.

![Figure 1: The CO2QUALSTORE stage-gate process for the selection and management of CO₂ storage sites [1].](image-url)
The approach described in Figure 1 is designed to facilitate the following:

- overall project risk management by providing storage related stage gates that may be coordinated with CO₂ capture and transport activities and approval processes by CCS authorities;
- best practice project development and operation from the CCS industry;
- the selection of safe and reliable storage sites that will provide the required storage capacity;
- the operation of the storage facility and the subsequent transfer of responsibility to a state authority.

The methodology described in this paper is particularly related to the third point above and has been applied by Vattenfall prior to the M2 and M3 milestones shown in Figure 1. These assessments have identified current risks and knowledge gaps related to the storage sites in question and laid the groundwork for developing site characterization work programmes. According to the CO2QUALSTORE guideline these work programmes should be designed to close the gap between the current state of knowledge, as determined by a risk/uncertainty assessment, and the criteria established by the project developer for passing the next stage-gate, or milestone. Site characterization is typically an iterative process between the M2 and M3 milestones.

In addition to defining the objectives of site characterization work, the risk assessment methodology presented here is also the first step in establishing risk management practices that will follow a project through its full life cycle. The CO2QUALSTORE guideline provides a framework for doing this and describes documentation required to enable transparency and traceability in the iterative risk assessment process during the project lifetime.

4. Risk assessment methods

Geological storage of CO₂ is a relatively new and developing technology, and as such does not have a historic knowledge base from which to extract experiences regarding risk assessment issues. Thus, the methods and tools used for risk assessment of CO₂ storage are largely adapted from risk assessments conducted for other substances. National or regional regulations set the context for risk management of CCS projects, including risk assessment, and may either be procedural or performance-based in nature. Both approaches make use of a performance goal, but in a procedural approach such a goal is not directly specified by the regulations. Instead, the regulations prescribe what an operator must do in order to reach an implicit performance goal, for example how a well must be constructed to avoid groundwater contamination. In a performance-based regulation an operator is directly responsible for achieving an explicitly stated performance goal and must convince the regulator of their ability to do so. The CO2QUALSTORE guideline advocates the use of a performance-based system for assuring CO₂ storage integrity and the risk assessment methodology presented here is designed to support this approach.

4.1. SWIFT method and semi-quantitative risk ranking

The SWIFT method is a flexible and efficient group-based approach to identifying potential hazards and uncertainties [11]. The technique was developed by DNV, in collaboration with GE Plastics and has been applied to a wide range of industrial activities from process engineering to heavy lifting operations, and more recently CO₂ storage. The latter evolution of the technique is the result of DNV’s work for the Norwegian Petroleum Directorate assisting the Norwegian government in the process of selecting the most suitable site for offshore CO₂ storage in Norway. The SWIFT method aims to meet the following objectives; to be comprehensive, to be efficient and to be proactive in identifying potential hazards. The distinctive features of SWIFT are that:

- it is able to identify hazards, evaluate risks in a qualitative sense, and recommend appropriate additional safeguards;
- it uses the expertise of a group with specialist knowledge of the activity under study;
- it follows a procedure that combines brainstorming, structured discussion and checklists;
- it considers the activity from a top-down perspective starting with systems or operations, rather than individual features, events or processes.

The discussions in the expert workshops are structured around the following categories of the storage complex;
reservoir, seal, overburden, vadose zone, surface, wells, fault zones and atmosphere. These categories have been selected by DNV as most appropriate for structuring the discussion around a site and were developed with basis in the categories present in the FEP databases that have been built by Quintessa [12] and TNO [13].

The SWIFT technique makes use of checklists to ensure that the exercise is comprehensive in identifying hazards. This is important because the purpose of SWIFT is to generate the input information to the remainder of the risk assessment workshop. The checklists that are used are specific to the categories under discussion in order to maintain the structure and focus of the workshop. The keywords originate from the Quintessa online database of Features, Events and Processes (FEP’s) [12] that is specifically designed for use with CO<sub>2</sub> storage site risk assessment. Quintessa developed the database in collaboration with the IEA Greenhouse Gas R&D Programme (IEAGHG) and the list of FEP’s it contains is recognised as being comprehensive.

The participants for such a workshop must be carefully selected in order to ensure that the spectrum of competencies covered by the team-members cover the key technical disciplines at this stage in the site characterisation process. Team members should be knowledgeable within their area of expertise and should be encouraged to be responsive and proactive during the risk assessment sessions.

The following points were discussed for each identified hazard and recorded:

- Causes - usually a few illustrative ones that could be cross-referenced to other hazards.
- Consequences - the main types of harm that might result if the hazardous feature, event or process occurred. It is important to discuss the potential consequences, and not to dismiss them on grounds such as low probability.
- Safeguards – potential or existing measures to avoid the hazard or mitigate its effect.

### 4.1.1. Probability and consequence

In order to assign semi-quantitative values of probability and consequence it is necessary for the experts to have a common understanding of the meaning behind each numerical value. For this purpose DNV has established reference tables that prior to application to specific projects are additionally tailored to meet project risk acceptance criteria and risk management requirements. When choosing a numerical value to represent probability or consequence the experts are encouraged to be conservative in their approach and thus avoid underestimating the potential risk associated with a given hazard. The interval of opinion is recorded in the case that agreement between the experts could not be reached or there would be uncertainties due to information available. When entering into the initial risk register the most conservative value that is proposed should be used. Examples of typical reference tables are shown in Table 1 and Table 2.

Table 1: Probability examples for semi-quantitative risk ranking. This table can be used as a reference by the experts when assigning probability values in the semi-quantitative risk ranking exercise. Note that Events are characterised by a frequency, while Features and Processes are characterised by a probability.

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Event (E)</td>
<td>Very unlikely to occur during the next 5000 years</td>
<td>Very unlikely to occur during injection operations</td>
<td>Likely to occur during injection operations</td>
<td>May occur several times during injection operations</td>
<td>Will occur several times during injection operations</td>
</tr>
<tr>
<td></td>
<td>Frequency</td>
<td>About 1 per 10000 years or less</td>
<td>About 1 per 1000 years</td>
<td>About 1 per 100 years</td>
<td>About 1 per 10 year</td>
<td>About 1 per year or more</td>
</tr>
<tr>
<td></td>
<td>Feature (F) / Process (P)</td>
<td>Disregarded</td>
<td>Not expected</td>
<td>50/50 chance</td>
<td>Expected</td>
<td>Sure</td>
</tr>
<tr>
<td></td>
<td>Probability</td>
<td>Less or equal 1%</td>
<td>Less or equal 10%</td>
<td>Less or equal 50%</td>
<td>Less or equal 90%</td>
<td>Less or equal 99%</td>
</tr>
</tbody>
</table>
Table 2: Consequence examples for semi-quantitative risk ranking. This table can be used as a reference by the experts when assigning consequence values in the semi-quantitative risk ranking exercise.

<table>
<thead>
<tr>
<th>No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Name</td>
<td>Very Low</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Impact on</td>
<td>Small temporary</td>
<td>Small reduction,</td>
<td>Significant</td>
<td>Significant</td>
</tr>
<tr>
<td></td>
<td>Injectivity</td>
<td>reduction. No</td>
<td>minor interruption</td>
<td>temporary</td>
<td>permanent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>interruption to</td>
<td>to injection (hours)</td>
<td>reduction,</td>
<td>reduction,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>injection</td>
<td></td>
<td>interruption to</td>
<td>new injectors</td>
</tr>
<tr>
<td></td>
<td>Impact on</td>
<td>Small chance of</td>
<td>Minor reduction in</td>
<td>Significant</td>
<td>Significant</td>
</tr>
<tr>
<td></td>
<td>Capacity</td>
<td>reduced capacity in the</td>
<td>capacity, does</td>
<td>reduction in</td>
<td>reduction in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>future</td>
<td>impact project</td>
<td>capacity, fixable</td>
<td>capacity, fixable</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>viability</td>
<td>without new wells</td>
<td>with new wells</td>
</tr>
<tr>
<td></td>
<td>Impact on</td>
<td>None</td>
<td>Unexpected migration</td>
<td>Unexpected migration</td>
<td>Leakage to vadose</td>
</tr>
<tr>
<td></td>
<td>Storage</td>
<td></td>
<td>of CO2 inside the</td>
<td>of CO2 outside the</td>
<td>zone over small</td>
</tr>
<tr>
<td></td>
<td>Integrity</td>
<td></td>
<td>defined storage</td>
<td>defined storage</td>
<td>area (&lt;100m²)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>complex</td>
<td>complex</td>
<td></td>
</tr>
</tbody>
</table>

4.2. Framework for assessing quality and uncertainty of geological barriers

The method for assessing the quality of, and uncertainty in, geological barriers focuses on primary and additional containment and is conducted on an individual basis by the experts after completion of the risk workshop described in 4.1. This barrier analysis method has been adapted from the Screening and Ranking Framework (SRF) for CO₂ storage sites that was developed at the Lawrence Berkeley National Laboratory [14], [15]. The method is semi-quantitative and relies on expert opinion to generate numerical input in response to a spreadsheet questionnaire.

The SRF was originally designed to be used for comparing the attributes of two or more potential sites. DNV has adapted it to enable gauging the range of expert opinion concerning a single location. This has been done via re-programming of the analysis spreadsheet and separating the input data forms from the analysis engine to allow for multiple data entry by the workshop participants. There are three objectives for making use of the framework:

- to record each experts’ opinion on these barriers with respect to fitness of the site for CO₂ storage;
- to record each experts’ opinion on the uncertainty connected to the understanding of these barriers;
- to measure the degree of consensus amongst participants after the workshop with respect to both fitness and uncertainty.

4.2.1. Questionnaire

In order to collect the experts’ opinion the risk assessment methodology includes a questionnaire tailored for each specific project. In general the questionnaire is divided into three sections that correspond to the three fundamental characteristics of a storage site with respect to storage integrity; primary containment, secondary containment and leakage potential. Each of these characteristics is further divided into attributes that are described by their physical properties. Such attributes may include:

- reservoir/seal thickness
- lithology
- demonstrated sealing for CO₂
- lateral continuity
- distance below ground
- pressure
- tectonics
- hydrology
- existing wells
- fault permeability

The questionnaire spreadsheet records the experts’ input for the Weight, Attribute Property and the Certainty Factor for each attribute, as defined below:

- Weight (1 – 10): a numerical value that allows the experts to express an opinion about the relative importance of the Attributes;
4.2.2. Analysis method

After receiving the completed questionnaires from the experts, the numerical input is compiled into three spreadsheets that represented the Primary Containment, Secondary Containment and Leakage Potential. Within each spreadsheet the average values of Weighted Attribute Properties and average Certainty Factor are calculated for every participating expert. The individual results within each spreadsheet are then plotted on graphs of Certainty Factor vs. Attribute Property. The plot visualises the experts’ opinion about the quality of the storage site and the current state of knowledge, as illustrated by Figure 2. Altogether, the analysis method includes three graphs on Primary Containment, Secondary Containment and Leakage Potential, each populated with data points representing the expert’s opinion.

As a CO₂ storage project develops, expert’s opinion should be monitored on the fitness of the storage site and the uncertainties involved. Repeated assessments will also demonstrate how the consensus among the experts evolves throughout the project, being an important input in building confidence around the project.

4.3. Lessons learnt from the different case studies

Positive experience with the methodology described in this paper has lead to repeated deployments by both Vattenfall and DNV. Experience gained by both parties has led to further development of the method and the main lessons that have been learnt are described in the following sub-sections.

4.3.1. Importance of project knowledge

One conclusion from comparing the two completed workshops for Vattenfall is that the discussions among the experts in Denmark were more focused. One reason for this is that the expert participants in the workshop had a greater familiarity and prior understanding of the storage site in question, allowing consensus to be reached more efficiently around certain aspects of the project.

4.3.2. Number of expert participants

Another observation from these workshops is that the facilitation of the workshop becomes challenging if the expert group is larger than 15-20 persons. The expert group was significantly larger at the German workshop that involved main industrial/research/academic stakeholders and relevant authorities, in total 25 experts. This
facilitation was demanding, but this drawback was outweighed by a broader range of expertise. Future development of the methodology should include streamlining to handle larger expert panels.

4.3.3. Risk and uncertainty assessment findings should help define future data acquisition needs

The risk assessment method should distinguish between risks that could be managed with targeted data acquisition and risks that could be handled by introducing technical safeguards. This ensures that the data acquisition programme and the detailed monitoring plan are designed in a way that addresses the risks in a proper and efficient way.

4.3.4. Risk and uncertainty assessment findings from the storage sub-project should be integrated into the CO₂ capture and transport

It is important that risks identified at an early stage of the CCS project are integrated with the risk management process for the CCS project as a whole. Clearly, risks related to the storage leg of the CCS value chain could be of such a character that it might jeopardize the whole project.

5. Risk management of CGS projects in Vattenfall

In the deployment of CCS projects, it is essential that project developers have a high-level understanding of the technical aspects that follow from establishing CCS as part of the value chain of fossil-fuel based power production. This is much assisted by well-acknowledged industrial standards, where the CO₂QUALSTORE guideline is one example.

There are a number of reasons for project developers to apply these standards. The internal company benefits include advice on quality assurance, logic work-flows with well defined decision points that assists budget planning, integrated time-schedules, and formal reporting plans (documentation). The additional external benefits are related to enabling external stakeholders to understand and follow how a storage development project is executed. Further, projects have wider credibility if it is clear that society’s expertise have been taken into account, i.e. through the engagement of this expertise in building the standard, either directly or indirectly through a thorough review process (which is the case for the CO₂QUALSTORE guideline). Altogether, working in accordance to well-acknowledged standards assists the communication of projects.

Vattenfall is well underway in developing a demonstration CCS project in Germany. At the Jänschwalde power plant, both Oxyfuel and Post-combustion CO₂ capture will be demonstrated on a large scale. Different storage options are currently being investigated [16]. In Denmark, Vattenfall is developing the storage part of a possible later commercial CCS project. Post-combustion capture at the Nordjyllandsværket power plant would be transported in a 30-kilometre pipeline to the Vedsted underground structure for storage [17]. Since the merger with NUON, Vattenfall also has CCS activities in the Netherlands.

In both the Danish project and the German project, early risk assessments have been carried out with the objective to develop risk registers that have guided the project development in terms of risk mitigation activities and as guidance to develop programs for the data collection needed in as part of the continued characterisation phase of the projects, as well as providing basis for developing base-line monitoring concepts. An update of the German storage project is underway later this year. This will show how well the project development has managed to mitigate the identified risks. Later updates are planned, enabling iterative cycles of risk and uncertainty assessment and evaluation.

The results of the risk assessments and reservoir simulations are used as the basis for the design of a detailed monitoring plan. A first monitoring plan for the Vedsted site in Denmark was developed by CO₂GEONET on behalf of Vattenfall in 2009 [18]. This monitoring plan – attributed version 0 – will be updated along with the progressing of the project.
6. References


