Dossier

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Dossier

Characterization of European CO_2 Storage – European Project SiteChar
Caractérisation de sites européens de stockage de CO_2 – Projet européen SiteChar

CO_2 Storage Feasibility: A Workflow for Site Characterisation

Manuel Nepveu[1], Filip Neele[1]*, Florence Delprat-Jannaud[2], Maxine Akhurst[3], Olivier Vincké[2], Valentina Volpi[4], Ane Lothe[5], Suzanne Brunsting[6], Jonathan Pearce[3], Anne Battani[2], Axelle Baroni[2], Bruno Garcia[2], Cor Hofstee[1] and Jens Wollenweber[1]

[1] TNO, Princetonlaan 6, 3584 CB Utrecht - The Netherlands
[2] IFP Energies Nouvelles, Rueil-Malmaison - France
[3] BGS, Nottingham - United Kingdom
[4] OGS, Trieste - Italy
[5] SINTEF Petroleum Research, Trondheim - Norway
[6] ECN, Amsterdam - The Netherlands
e-mail: filip.neele@tno.nl

* Corresponding author

Abstract — *In this paper, we present an overview of the SiteChar workflow model for site characterisation and assessment for CO_2 storage. Site characterisation and assessment is required when permits are requested from the legal authorities in the process of starting a CO_2 storage process at a given site. The goal is to assess whether a proposed CO_2 storage site can indeed be used for permanent storage while meeting the safety requirements demanded by the European Commission (EC) Storage Directive (EU, 2009, Storage Directive 2009/31/EC). Many issues have to be scrutinised, and the workflow presented here is put forward to help efficiently organise this complex task.*
Three issues are highlighted: communication within the working team and with the authorities; interdependencies in the workflow and feedback loops; and the risk-based character of the workflow. A general overview (helicopter view) of the workflow is given; the issues involved in communication and the risk assessment process are described in more detail. The workflow as described has been tested within the SiteChar project on five potential storage sites throughout Europe. This resulted in a list of key aspects of site characterisation which can help prepare and focus new site characterisation studies.

Résumé — Faisabilité du stockage géologique du CO_2 : une méthodologie pour la caractérisation des sites de stockage — Dans cet article, nous présentons un aperçu de la méthodologie développée dans le projet SiteChar pour la caractérisation et l'évaluation des sites de stockage de CO_2. Caractériser et évaluer le site potentiel de stockage sont deux étapes nécessaires dès lors qu'un permis de stockage est requis par des autorités légales dans le processus de lancement d'un projet de stockage de CO_2 sur un site donné. L'objectif est d'évaluer si le site de stockage de CO_2 proposé peut en effet être utilisé à des fins de stockage permanent tout en répondant aux exigences de sécurité imposées par la Directive sur le stockage de CO_2 de la Commission Européenne (CE) (UE, 2009, *Storage Directive* 2009/31/EC). De nombreux aspects doivent

être investigués, et la méthodologie présentée dans ce papier apporte une aide pour organiser efficacement cette tâche complexe.
Trois points sont soulignés dans cet article : la communication au sein de l'équipe de travail et avec les autorités, les interdépendances entre les différentes étapes de caractérisation et les retours d'information et la spécificité de l'approche basée sur une analyse de risques. Une vue d'ensemble de la méthodologie est donnée ; les questions liées à la communication et au processus d'évaluation des risques sont décrites plus en détail. La méthodologie, telle que décrite dans le papier, a été testée dans le projet SiteChar sur cinq sites de stockage potentiels répartis en Europe. Il en a résulté des éléments clés de la caractérisation de site de stockage de CO_2 susceptibles d'aider à préparer et investiguer de nouvelles études de caractérisation de site.

INTRODUCTION

The large-scale introduction of Carbon Capture and Storage (CCS) for fossil-fuelled electricity generation and at large industrial plants is needed in order to curtail CO_2 emissions and help prevent future adverse consequences due to the effects of climate change (IEA, 2013). The storage capacity of deep geological (sedimentary) formations is sufficient to store CO_2 emission for several decades into the future (IEA, 2013). Storage capacity is available in depleted gas and oil fields and in deep saline formations. It is essential for the development of large-scale CCS that a sufficient reserve of proven and qualified storage capacity is available at any time, to provide certainty of storage for capture plants (Bachu *et al*., 2007; Vangkilde-Pedersen *et al*., 2009; Neele *et al*., 2012).

The development of a storage site, which includes exploration, characterisation and infrastructure development for CCS, is a time-consuming and complex process. While the development and building of a capture plant is the most capital-intensive part of a CCS project, the long lead time associated with the development of a storage site is likely to constrain the timing of its development. It is therefore essential to start characterising the storage sites as early as possible in the development of CCS projects.

For any practical case the emphasis naturally lies on the operational issues. The more abstract workflow and its issues are not always described in full. For instance, in the Goldeneye project (ScottishPower CCS Consortium) documentation on purely technical issues is abundant, while workflow issues are barely addressed (UK Carbon Capture and Storage Demonstration Competition, 2011). Also, in the QUEST project (Canada) by *Shell* no information of this more abstract nature was found (www.//shell.ca/en/aboutshell/our-business-tpgk/upstream/oil-sands/quest.html).

In this article, then, we address the more generic points of such a workflow.

One of the central goals of the European Commission 7th Framework Research (EU FP7)-funded project SiteChar was to develop a workflow for site characterisation and risk assessment studies for the store of CO_2 under the EU Storage Directive (EU, 2009)[1]. It defines the work to be done to comply with the EU Storage Directive (EU, 2009), resulting in efficient site characterisation studies, to be presented to the authorities when applying for a storage permit. This workflow was applied to five potential storage sites (Akhurst *et al*., 2015; Beaubien *et al*., 2015; Gruson *et al*., 2015; Brunsting *et al*., 2015; Volpi *et al*., 2015); the experience thus acquired was used to update and improve the workflow.

This paper provides a summary of the workflow, highlighting issues that are of paramount importance in a well-conducted characterisation and assessment study. The lessons learnt during the actual application to potential storage sites are discussed. This article presents an overview; for details the reader is referred to the original report (Neele *et al*., 2013).

1 BACKGROUND

Several studies have been completed that address site characterisation for geological CO_2 storage (SAMCARDS, 2003; CO2CRC, 2008; DNV, 2009; NSBTF, 2009; NETL, 2010; Neele *et al*., 2011; Wollenweber *et al*., 2013). The studies describe, to a varying level and degree, the work to be done to include all aspects relevant to safe and secure geological storage of CO_2 in a specific formation. In these reports, the central role of risk assessment and management is generally emphasised.

As part of the efforts to streamline the development of CO_2 storage sites and the development of CCS in

[1] This workflow was presented in deliverable D1.4 of the EU FP7 project SiteChar (Neele *et al*., 2013) (henceforth called the SiteChar report).

general, standards for the storage of CO_2 have been published, in Canada (CSA, 2012) and in Europe (DNV, 2012). Both standards cover the complete lifetime of a storage project, from screening until and including site closure.

However, a number of aspects of the site characterisation process are not or only partly covered:

- the sequence of the different steps and the timing of the process. Some of the steps in a site characterisation study are time-consuming and likely to determine the critical path;
- interdependencies and feedback loops within the process. The activities in a site characterisation study are strongly interlinked, creating an iterative process. This calls for an efficient flow of information between the different disciplines;
- the coverage of the different requirements of the EU Storage Directive (EU, 2009) in the process. The EU Storage Directive lists a number of aspects to be assessed for a storage site. While some explanation is given in the Guidance Documents (EU, 2011), no clear explanation is available of how to address the EU Storage Directive aspects with results obtained in a site characterisation study.

The above-mentioned SiteChar report (Neele *et al.*, 2013) explicitly addresses these points.

2 THREE FOCAL POINTS

Three issues that play a significant role within the workflow are described in the following sections.

2.1 Interplay between the Operator/Competent Authorities

Apart from the technical aspects of defining a workflow there is an important non-technical issue; the interplay between the operator of a prospective site and the "Competent Authorities" (CA) as mentioned in the EU Storage Directive (EU, 2009). The identity of the operator who will perform a site characterisation is clear enough; who the CA are depends on the national laws in force at the site under scrutiny. In the following, it is assumed that the CA are clearly identified in any specific situation. In a formal document such as the EU Storage Directive (EU, 2009) the CA feature at formal moments in the process that may lead to CO_2 storage, for instance when the site operator hands in documents required for a specific license.

Indeed, the characterisation and assessment is required by the EU Storage Directive (EU, 2009) in a formal permit application to the CA for CO_2 storage at a given site. The guidance documents on "Implementation of Directive 2009/31/EC on the geological storage of carbon dioxide" (EU, 2011) are a much welcomed addition as they advise the CA on how to perform their tasks at such moments, and what issues should have their full attention. However, it has become increasingly clear that the contacts between the operator and the CA cannot remain restricted to formal moments in time. Section 4 elaborates on this recommendation.

2.2 Interdependencies and Feedback Loops

The screening process results in a list of potential candidates for CO_2 storage, and in the end one or more specific sites are chosen, assumed to be suitable for storage.

Especially when the various geo-scientific disciplines are invoked in the quantitative aspects of site characterisation, a strictly linear workflow (*i.e.* without loops) is an illusion. For instance, new data or intermediate results may necessitate changes in the 3D static earth model, which then may have consequences for the reservoir engineer studying the fluid dynamic properties of the potential storage strata. These new results may raise further questions for the geologist, leading again to adaptations. The iterations depend on the specific properties of the site and cannot be listed at a generic level.

2.3 Risk-Based Workflow

Risk Assessment is the driver for the characterisation process. It is the process of identifying risks/scenarios that might be adverse to storage site performance and human safety and the environment. The risks as perceived by a multidisciplinary team of experts guide the work to be done. A qualitative overview is the starting point, based on general and site-specific knowledge concerning features, events and processes that may play a role. Qualitative Risk Assessment accompanies the characterisation process all along. If new and unexpected risks turn up in the course of the quantitative work it will feature as part of a feedback loop. The qualitative and quantitative aspects of risk assessment are intertwined. Section 5 deals with the Risk Assessment (RA) process.

3 THE WORKFLOW IN HELICOPTER VIEW

Figure 1 shows a graphical representation of the workflow. The arrows represent the flow of the work activities and of information. The figure contains a number of iterations. These are feedback loops, schematically shown in the figure through arrows that point back towards an

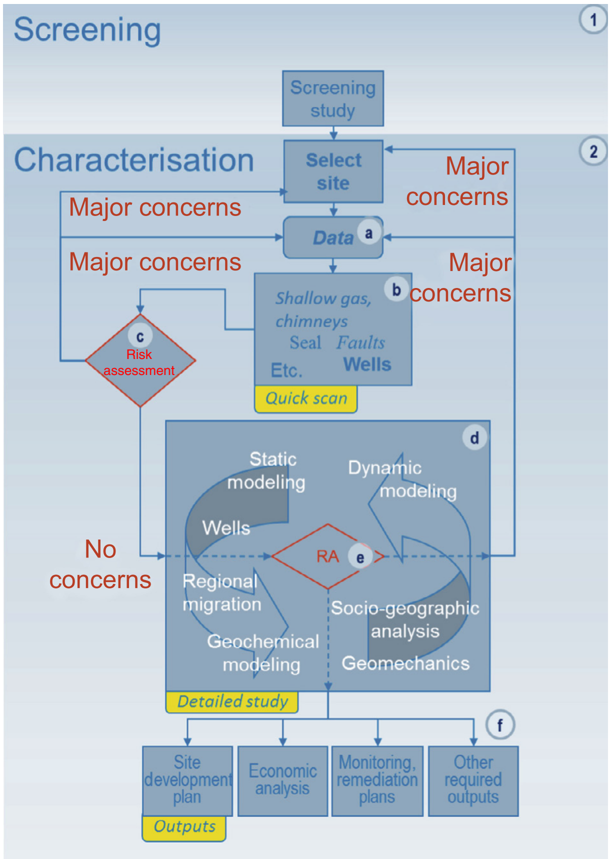

Figure 1

Workflow of site screening and characterisation. The numbers and letters in circles refer to the list in Section 3.

'earlier' stage in the general flow. Diamonds represent RA decision points.

A site characterisation study generally starts with a screening and selection study of potential sites, in which the options for storage in a given area or region are investigated.

A site characterisation study is similar to work done in oil and gas exploration, although in the case of CCS the focus and area of study are different. While in oil and gas exploration the emphasis is put on the reservoir, a CO_2 storage feasibility study must qualify the storage complex, which includes not only the reservoir, but also the cap rock and the overburden and side burden strata. In the case of CO_2 storage, the ability of a geological structure to trap and retain CO_2 permanently must be demonstrated. Given the geological uncertainties, the aim of a site characterisation study is to estimate the risks that accompany CO_2 storage in a given storage complex and whether remediation programmes can be conducted.

The areas of expertise that must be covered by the team (and that are shown in the large box in *Fig. 1*) include:

- structural geology/sedimentology/petrophysics,
- reservoir engineering,
- geomechanical modeling,
- geochemical analysis and geochemical modeling,
- well engineering,
- risk assessment,
- social analysis,
- environmental impact assessment.

Apart from these areas, additional areas of expertise may be required to obtain further results to prove a site's suitability for storage:

- economic analysis,
- engineering and design of injection facilities.

3.1 Screening Study

This is a high-level investigation of all options for CO_2 storage in a specific area or region. This screening may be undertaken by operators or by the CA in preparation for leasing potential areas for storage. Typical screening criteria are derived from CO_2 storage itself (such as depth of the formation), from the capture installation (volume of CO_2 to be stored, rate, timing), and economic considerations (distance from the capture plant, cost of storage, other uses of the pore space). RA starts already in the screening phase, as any risks perceived at this stage must be taken into account; these include the existence of old and/or abandoned wells and interference with other activities in the subsurface and at the surface. Other aspects should also be included at this stage, such as environmental and societal restrictions. Experts form an opinion on available data and use knowledge of a general nature. Overall geoscientific knowledge of the region is an important part of the input and of the decision-making. At present some general rules of thumb are available that allow some rough preliminary estimates; see, for example (Ramirez *et al.*, 2010).

The expected output of the screening phase is a list of promising potential storage sites. The next step, characterisation and assessment, is intended to either elevate such sites to the status of "suitable", or dismiss them.

3.2 Site Characterisation Study (Including Assessment)

The elements of the site characterisation are described in some detail, following the numbering in Figure 1.

a) The first step in the characterisation study is to collect all available data on the site, in addition to the data collected for the screening phase. For a depleted hydrocarbon field, there is usually not much shortage of existing data. Well data, production data and reservoir models may be available. For saline formations, the situation may be quite different. In some cases, the saline formation is associated with hydrocarbon production and wells may penetrate the formation, with well logs and other data available. In the case of a virgin formation, with few or even no wells penetrating the formation, this first step might involve active data collection; shooting a seismic survey; and collection of data from publications or observations of the formation, where exposed, or of similar formations. The role of the CA is to ensure that the data collected are sufficient to give potential evidence of the storage prospect. The CA should view the data with respect to their completeness for the characterisation and assessment as intended;

b) A quick analysis then follows. The aim of this step is to identify any problems related to the site before the study is continued. All available data are scrutinised, so as to find anything that could impede safe and secure storage, or that could affect the site's ability to meet the storage requirements;

c) A qualitative RA has to be done as a first step in the characterisation phase. The quick analysis is followed by a workshop with the specialists from the team, who define the risks associated with the site. These risks are related to the safety and security of storage, as well as the conformity with storage requirements. The aim of this step in the workflow is to identify whether there are aspects that render storage at the site unviable, and whether additional data is to be collected. A semi-quantitative step based on expert input may point to the risks with the highest probability of occurrence (Nepveu *et al*., 2009);

d) When this first qualitative RA is passed, the site is studied and modeled in the different areas of expertise. This is represented by the large box labelled 'Detailed study' in Figure 1. The figure lists a number of highlights from the respective areas. This is the most time-consuming and also the most complex part of the study, requiring intensive interaction within the team;

e) Once all aspects of safe and secure storage have been studied and once internal consistency in results and data is reached, the risk analysis can be made quantitative, *i.e*. HSE analysis can be performed (HSE stands for Health, Safety, Environment; HSE analysis concerns itself with quantifying risks in these areas). Risks are compared with an *a priori* determined risk threshold. Adequate mitigation actions are then envisaged so as to reduce risks. However, if risks are too high and mitigation measures cannot be taken or are too expensive, the site shall be discarded[2].

f) When the risks are deemed acceptable, the last elements of a site characterisation study can start. These elements include setting up a monitoring plan and baseline studies, drafting a site development plan, and analysing the costs of storage. The monitoring plan is a requirement for a storage site, defined in the Storage Directive (EU, 2009) and so is the development of a "corrective measures" plan, based on hazards that might occur. The site development plan is part of the activities of the future operator, but not formally required by the Storage Directive (EU, 2009).

The characterisation and assessment study is **risk-based** as well as **site-specific**. The (site-specific) qualitative risk assessment will act as a guide that pervades the study in all respects; it is "leading". Those scenarios that may lead to significant irregularities and are quite possible in the given, site-specific situation have to be investigated in detail.

The work of the expert team is to produce a so-called risk matrix. This is a diagram in which risks are positioned along two axes: probability *versus* severity. This graphic method indicates which risks have to be scrutinised in full measure; Figure 2. Produced in the first version in step 'c)' above, this risk matrix will guide the numerical work in the subsequent steps.

The required level of detail of scrutiny should be clear, as well as which theories and approximations of the different parts of the investigation are appropriate to reduce the uncertainties to acceptable levels.

When quantitative detailed analyses are undertaken, it is quite possible that new risks are discovered. In fact, any numerical investigation is not only directed at "getting numbers", but also at getting a fuller picture of what happens, and which processes unfold. If and when such new risks arise, the risk assessment and characterisation process has to be reiterated. For obvious reasons, the CA should be informed of the status and of changes in the risk matrix. In any case, the CA and the operator should agree on the scope and focus of the site characterisation work, so as to smooth the process, and avoid undue delays at the formal moments in the process of working towards a permit application.

[2] Note: in the SiteChar workflow HSE analysis is not described. It is a stand-alone activity that follows the RA and characterisation work, using CO_2 fluxes and timescales of surface emissions as input. Its outcome will not influence the other parts of the workflow by feedback loops.

Probability \ Severity	Very low	Low	Medium	High	Very high
Very high	0	0	0	0	0
High	0	2	4	2	0
Medium	0	4	18	8	0
Low	0	3	20	13	0
Very low	0	0	4	1	0

Figure 2

Risk matrix: probability *versus* severity. As an example, the number of risks is reproduced; in a full risk matrix the risks are described in detail.

4 COMMUNICATION ISSUES

4.1 Interplay between the Operator/Competent Authorities

In the EU Storage Directive (EU, 2009) the CA feature at formal moments in the process that may lead to CO_2 storage. However, it has become increasingly clear that the contacts between the operator and the CA cannot remain restricted to formal moments in time. The annexes to the EU Storage Directive (EU, 2009) suggest a sizeable programme of research to be conducted, However, in any specific situation some aspects of the storage complex need to be studied in more detail than others. It has to be decided in an interplay between the operator and CA which research is deemed necessary and sufficient in order to comply with the requirement of the Storage Directive (EU, 2009) that a geological formation and its surroundings shall be characterised and assessed as suitable for storage. No significant risk of leakage, and no significant environmental or health risk should exist for such a formation to be eligible as a storage site. For this reason, the interplay between the operator and CA should have a more continuous character, the formal moments in the process remaining as they are. Continuous interplay will lead to a better understanding by the CA of the site-specific characteristics; it will lead to a focus on the activities to carry out for a permit application – what the operator should deliver at the formal moments in the process. The risk matrix will act as the central item to be discussed between the CA and the operator.

Characterising and assessing a prospective site is rather different from characterising and assessing a chemical plant. Whereas the construction and structure of such a plant can be known to the finest detail, the subsurface clearly cannot. No amount of data can render a 3D earth model undisputed to the finest detail. There is still the well-known dichotomy of high-resolution/strictly localised data (well-logging data) and low-resolution/global data (seismic survey data). Much, then, has to be filled in from the geologist's general background knowledge. The consequence is that a degree of subjectivity enters the process which can never be eradicated in full measure. Therefore, it is advocated to consider the characterisation process as a mutual concern of the operator and CA, even though these parties have different formal roles. The CA must build up trust that the operator is "doing the right things", given what is known of a site. The CA must have experts at their disposal who can take up such a communicative role.

4.2 Interplay of Disciplines

Interdependencies and feedback loops in the workflow play a significant role. This entails that communication between the different disciplines (their experts) must be attributed great significance. The interaction starts at the qualitative RA, which is necessarily a multidisciplinary investigation. When the quantitative work starts, there is the threat of different scientific disciplines becoming too isolated. Certainly, there are necessarily contacts between the disciplines on questions of desired input and output, but after that has been cleared, there is a phase where every discipline acts on its own. Here lies the danger of experts working in "splendid isolation".

The best way to mitigate this danger is to have a small committee installed that organises regular meetings with all the workers. These meetings will keep everybody informed on the development of the site characterisation, provide the information on whether the study is properly focused, and consider implications from results of one discipline on another field of survey. It should be decided beforehand how often such meetings are held.

These regular meetings act as a bond and facilitate the contact between different disciplines. This streamlines the workflow. Action plans must be formulated, as the discussions should lead to specific activities for the specialists involved. At the meetings the risk matrix (see *Sect. 3*) plays a central role. Are the known risks being brought down to acceptable levels? Have new risks been found as a result of the quantitative work? The whole team involved in the workflow thus stays informed of results and considers their implications as soon as they are obtained.

5 THE RISK ASSESSMENT PROCESS

5.1 Risk-Based Character of Site Characterisation

This section describes technical aspects of the workflow on a generic basis. The workflow is risk-based, with three generic risks: leakage through the seal, the wells, and along the faults. The workflow must first model the subsurface and the man-made structures (wells) in "standard mode" in which no leakages of any kind occur. Only when this preliminary phase has led to some understanding, and model(s) have been successfully obtained can the effects of the uncertainties established in the qualitative RA be studied. This leads to the definition of some particular risks.

5.2 Data Completeness, Sensitivity Analysis

Input data are never enough to fully constrain a model of the 3D subsurface. Uncertainties are generally large, as data derived from wells represent point measurements in a (very) large 3D volume, or represent measurements of subsurface properties taken from the surface (in the case of seismic data). Hence, we cannot rely on just a single digital representation of the storage complex. The key tool to address this issue is sensitivity analysis. However, by conducting a sensitivity analysis we touch on a generic problem: how many runs have to be performed, and how many 3D models are required? A provisional answer can be given with the help of the theory of dimensional analysis, displaying the order of magnitude of the work, *i.e.* the number of models to be run (Hanche-Olsen, 2004). Here this amount of work will become prohibitive, if each uncertainty has to be taken into account in full measure. Choices must necessarily be made. Hence, proper discussions between the operator and CA about the depth of the sensitivity analysis are recommended.

5.3 Continuous RA during Site Characterisation

Site characterisation will be undertaken in roughly this order:

1. data acquisition,
2. quick analysis,
3. qualitative RA,
4. geological assessment (static model building),
5. geomechanical assessment and potential for induced seismicity,
6. dynamic behaviour,
7. geochemical assessment,
8. migration path analysis,
9. well integrity analysis,
10. consequence analysis (health safety and environment, HSE).

Step 4 leads to steps 5 to 9, and steps 7, 8 and 9 can largely be performed in parallel. Steps 5 and 6 tend to be strongly linked. The given ordering is not carved in stone, but more important: returning to an earlier issue might be necessary on account of later emergence of unanticipated risks. Hence: we have to deal with a continuous risk assessment process.

5.4 Quantitative RA

In a quantitative RA, each of the different scenarios has to be considered and "carried" all the way through the steps identified above. The computations and results in one area of expertise should deliver relevant input for the next step. For each step the following questions are to be addressed:

- Which description ("theory", "mathematical model") applies in the different fields of expertise? What effects can be neglected? What effects should be included in any case? Which degree of accuracy is consistent with the available knowledge?
- What is the uncertainty associated with each parameter? It may become clear that many essential parameters are not well known. It is important, then, to perform a sensitivity analysis to find out which parameters most significantly affect the simulation results, and therefore merit further characterisation aiming at reducing their uncertainty. Intimately connected is the question of how many runs should be performed to cover the parameter space adequately;
- Which tools ("software packages") must be used? Tools must be robust and precise. The actual models may be only global in nature, nevertheless the calculations should give trustworthy results. Actually, global models, displaying trends rather than many, often uncertain details, are easier to handle in flow calculations. In addition, these models, when adequate, have the added bonus of producing precise results with much less computational effort.

The different steps have to interface with each other. If unexpected phenomena turn up within one of the disciplines it might be decided that a feedback loop should be established between two or more disciplines, complicating the simple linearity suggested above. In order to make this possible, it is vital to heed the points made in Section 4 on communication among the various disciplines.

5.5 Various Remarks

First, a few technical matters are addressed:

– in the end each model (each representation of the 3D subsurface) is analysed in the various steps. Thus, ultimately the information obtained on subsurface CO_2 migration and pressure development yields CO_2 flux densities and relevant timescales at the surface, if they occur at all; at that point HSE questions have to be addressed. Ideally many computations would have to be performed so that for all parameters that are indispensable for this task, one can establish a (joint) probability density function. This density function contains all information on uncertainties of the relevant parameters and their correlations. For instance, atmospheric CO_2 dispersion simulations can be done on the basis of the information in that density function about flux densities and the surface area and timescales involved;

– the concept of "probability" is important for the work presented here; it introduces itself naturally into the RA process that should deal with uncertainties. The SiteChar workflow implicitly adheres to the Bayesian interpretation of probability which accounts for our current state of knowledge, rather than "frequencies" of occurrence. The Bayesian interpretation is most natural within the workflow as proposed.

Finally, there is an important legal issue that should be pointed out: Article 4.4 of the Storage Directive (EU, 2009) states that "A geological formation shall only be selected as a storage site, if under the proposed conditions of use there is no significant risk of leakage, and if no significant environmental or health risks exist". Clearly, the intention is permanent storage. How the assessors should demonstrate this status is not specified in the directive. In fact, it is not specified what "significant risk" should mean in practical terms. The level of abstraction of the Storage Directive (EU, 2009) forces the national authorities to interpret and understand the results of the site characterisation study in terms of 'significant risk'. For a more complete list of points that need a "translation" in practical terms the reader is referred to Lako *et al*. (2011).

5.6 Critical Path of Site Characterisation Study

The critical path of a RA project is defined by the acquisition of the necessary data plus the modeling sequence of static geological assessment and dynamic simulation of the CO_2 injection process.

The experience from the SiteChar partners is that steps 1 (data acquisition), 4 (static model building) and steps 5 and 6 (geomechanical assessment and dynamic behaviour, respectively) often define the duration of the site characterisation process.

6 KEY ISSUES IN A SITE CHARACTERISATION PROCESS

The Sitechar workflow describes the tasks done within the different disciplines, the required input and output, the interconnections, and the interactions among the various disciplines. The lessons learnt by actually performing site characterisation on the different SiteChar sites are summarised here. In part they reiterate issues already discussed, in part they are technical.

6.1 Key Points Related to Static Model Building

Static model building is particularly important, since its output is the basis of all further steps in site characterisation. The better the static model, the more relevant the subsequent steps in the various disciplines.

Data. High-quality data are needed in sufficient abundance and with a spatial distribution that allows characterisation of the various geological components of the storage site. Data from hydrocarbon wells are of particular importance as well as the coverage and vintage of the seismic data. Data on the petrophysical characteristics of lithological formations obtained from the wells are very important. Spatially unequal coverage is a serious drawback.

How many static models? Multiple static models might be called for if the structural configuration of the site is not entirely clear (*e.g*., are there faults clearly seen from the data, or is it a matter of interpretation?). This clearly adds to the workload. An alternative is to successively update the static model as deemed necessary from the inputs/requirements of the other disciplines.

Model extent. The model should encompass the volumes that might contain CO_2 in steady state. A practical way might be to construct a detailed model of the reservoir (containment volume) with its overburden/underburden, whereas the laterally equivalent strata are modeled on a coarser grid. Potential CO_2 migration paths should be modeled with different tools, and the results compared and discussed.

Model resolution. The resolution of the model depends on the data resolution. However, it should be kept in mind that if lateral resolution is not an issue, simulation of CO_2 migration calls for a grid with coarse-scale horizontal resolution. Grid refinement at and around wells/faults should be possible. It would be a bonus if the static model could be updated easily in this respect. Vertical gridding could be coarse in the overburden/underburden, depending on the geological variability.

Software used. Commercially produced standard industry software is strongly recommended in the different fields of expertise (such as static model building and dynamic modeling). That software is widely used, has been developed and tested extensively and the export facilities to different tools and formats are well developed. Nevertheless, exchange of data between different software tools remains a crucial issue. This should be tested and proven at the very beginning of the RA activities.

Collaboration between different experts. This issue has been dealt with earlier on a general level. A number of practical, related issues are listed here:

1. different software as used by different research groups can require model manipulation for obtaining compatible formats. Distortions of the original can result;
2. the static model has to be built by working together with the dynamic modelers from the start of the project. Fluid simulations can be quite sensitive to vertical grid and model cell attribution; this point should be taken up in this cooperation;
3. exchange of information on different software proposed to be used has to take place as soon as possible. Important in this respect are the issues on input/output formats;
4. importantly: the CO_2 storage concept should be well known by the team, and the overall research should be planned carefully, and this requires the relevant site-specific questions to be asked. This emphasises the need for a good basic understanding of the proposed storage site, and this again shows the importance of a thorough qualitative risk assessment early on.

Data acquisition:

1. licensing and acquisition of data can take a long time, up to several months, and should be started as soon as possible. Significant effort may be needed to review and select the data;
2. significant cost may be involved in acquiring new data (such as seismic survey data, drilling a well and acquiring well logs);
3. data might have unequal areal coverage;
4. there are always conversion issues (formats), especially with legacy data. Converting data to formats used by modeling tools may require significant effort;
5. in depleted oil/gas fields there are abundant data, but sifting them as to relevance requires quite some effort. In saline aquifers, there are not so much data already available generally. They have to be obtained and in that process some assumptions must be made (*e.g.* on spatial sampling resolution).

Altogether the static model building appears a most critical phase: data gathering and contacts with different specialists from other disciplines make it a time-consuming step in the site characterisation process.

6.2 Key Points Related to Dynamic Modeling

The following points merit special attention in dynamic modeling:

1. Coordination between different experts. There is a need for close interaction with the static modelers, in order to streamline and iterate parameters for the dynamic simulation scenarios. Close interaction with geomechanical modelers is also needed, to agree on injection scenarios, and the use of compatible modeling software;
2. It is advisable to consider dynamic and geomechanical modeling as coupled processes that must be modeled simultaneously;
3. The injection scenarios should be discussed and agreed with the operator. There is a direct link between cost of injection and the choice of injection scenarios, through the number of wells and injection sites involved;
4. It is important to define appropriate boundary conditions, especially when comparing regional and local model simulations;
5. Data availability is always a major concern:
   - the collection of data should start early, as it is a time-consuming process;
   - there is a considerable added value in the participation of the hydrocarbon field owner, to have access to detailed reservoir properties. Especially, relevant information on reservoir heterogeneity is much welcomed, as it is highly relevant input for the static modeling, pressure history and fluid properties for the dynamic modeling;
   - fault behaviour is key information. Here sensitivity analysis is strongly advised as fault properties are not generally well known.

6.3 Key Points Related to Geomechanical Modeling

1. Appropriate pressure and temperature conditions at the reservoir boundaries (or perhaps farther away) need to be known; they serve as boundary conditions in the computations;

2. Availability of data is an issue. In particular:
   - information on fault properties,
   - initial stress state,
   - overburden properties,
   - proneness to seismicity, from past records;
3. Assumptions must be shared explicitly among the team of experts;
4. There is a need for close operation with the dynamic modelers:
   - geomechanical modeling establishes crucial seal rock fracture pressures, which is a constraint on the injection scenario(s). Such modeling may also inform on the likelihood of induced seismicity during injection, and perhaps after closure;
   - coupled dynamic and geomechanical modeling is needed;
   - consistency of models must be ensured;
   - software/format compatibility must be assured before commencing dynamic and geomechanical modeling.

6.4 Key Points Related to Geochemical Modeling

1. A good understanding of the mineralogy of the reservoir is essential for a reliable geochemical study. Core analysis from the immediate vicinity is important. Formation water composition and property data may have to be assumed, if not available;
2. There is a need for the evaluation of geochemical modeling software that accommodates reactions in oil and gas and water-bearing strata (if relevant).

6.5 Key Points Related to Well Integrity Analysis

1. Availability of appropriate data:
   - analysis of the status of existing wells can only be done when real data are available (e.g., status of the cement, well casing);
   - *in situ* observations of wells are required. Such operations are expensive. Cost estimates and timing of such operations should be addressed as early in the process as possible;
   - information on well cement and other well material is often not available. This is problematic and hampers reliable well integrity modeling;
2. There may be a need to study a worst-case scenario where real data is not available and estimate the associated risks, to side-step the problem of a lack of data.

6.6 Key Points Related to Migration Path Analysis

1. The timing and the volume of CO_2 migration should be quantified for a proper risk assessment and to define preventative measures;
2. Information on fault properties is important;
3. An iteration may be needed with dynamic modeling that is related to spill points identified by the migration path analysis.

CONCLUSION

This paper describes the SiteChar project workflow for a site characterisation study for CO_2 storage, as required for a storage permit application under the EU Storage Directive (EU, 2009).

The key points in a characterisation and assessment study are the following:

1. The characterisation study intends to fulfil the obligations laid down in the EU Storage Directive (EU, 2009). Two parties are directly involved: the operator of the prospective site and the so-called Competent Authorities. Next to the formal moments of contact between them, as indicated by the Storage Directive (EU, 2009), it is essential that the parties have regular contact. These contacts will inform the operator on what is expected from them in the study, on the basis of the national implementation of the EU Storage Directive (EU, 2009). They must also lead to a fuller understanding of the prospective site by the CA, who are to define the actions to be performed by the operator. The interaction should speed up the process that will lead to exploration and storage permits when appropriate;
2. The process is risk-based. A preliminary (qualitative) risk assessment is performed in the screening phase; if the potential site meets the requirements, a more thorough investigation of the risks and uncertainties (moving towards a quantitative risk assessment) is undertaken during the site characterisation study. The expert team defines risks and associated adverse scenarios and the work should always be based on the risk assessment and risk ranking. The risk matrix will form the central issue in the contacts between the CA and the operator. The detailed site characterisation, numerical in nature, should be expected to uncover relevant new risks that were not anticipated earlier. These risks must lead to reiteration. It is advisable that the parties involved agree on a protocol to be followed in such cases;
3. The characterisation study is multidisciplinary. It should encompass a quick scan, qualitative risk assessment, static modeling, dynamic modeling, geochemical analyses and modeling, geomechanical modeling, well integrity analysis, migration path analysis, socio-geographic analysis, and quantitative risk analysis. The focus of the activities in each

discipline is strongly site-specific and should be based on the risk assessment;

For completeness the following point is added.

4. Further activities that follow from the characterisation and assessment are drawing up a monitoring plan, a corrective measures plan and a site development plan together with cost estimates. It is to be noted that the monitoring plan is also risk-based and site-specific.

The prime keywords in site characterisation are "risk-based" and "site-specific". This makes it difficult to generically specify all the actions to be undertaken by the investigators as if they are carved in stone: they are not. For the reasons above regular communication between the operator and CA is a practical necessity. In order to speed up the process of site characterisation and assessment such contacts are important as well.

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